DEVELOPMENT OF 15 PSI SAFE HAVEN POLYCARBONATE WALLS FOR USE IN UNDERGROUND COAL MINES

by:

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Final Report

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Introduction

The project team has successfully developed a 15 PSI safe haven wall system for use in underground coal mines utilizing polycarbonate panels and steel framing. The goal of the project was to create a more cost effective solution to current refuge alternatives while still providing the highest level of safety with the ability to expedite mine rescue teams' efforts in the event of an explosion. To accomplish this, the design incorporated expertise and materials from the civil construction industry which already uses many blast mitigation technologies. The use of blast resistant polycarbonate panels provide a light-weight and easily handled material for personnel constructing the safe haven walls. During construction of the prototype in an underground coal mine, there was far less material handling and transportation when compared to a block and mortar wall. The reduction of material handling may potentially reduce the number of slip/fall injuries which are among the most common injuries in underground coal mines.

To achieve structural safety and blast resistance, the safe haven wall system was designed and modeled in ANSYS Explicit Dynamics and AutoDYN to produce an adequate design capable of resisting a MSHA prescribed pressure versus time curve. The design was then modeled for its intended use in a coal mine environment using FLAC^{3D} to ensure reactions into the mine geography were sustainable. Following successfully modeled designs, a wall was manufactured and tested using the high explosive shock tube facility in Georgetown, Kentucky. After the system passed laboratory explosive testing, a field ready system was developed and installed in an underground coal mine in Kentucky. Once the wall design is considered permissible by MSHA, the wall designs will be a cost effective option for active coal mines to provide its miners a place to seek refuge in the event of an explosion.

Design and Modeling

Design and modeling began with development of a safe haven wall system that can resist a 30 PSI blast load spanning 200 milliseconds which gives a safety factor of two to the 15 PSI MSHA requirement. The MSHA prescribed curve has a linear increase to 15 PSI at 100 milliseconds and then decreases linearly to zero at 200 milliseconds (Department of Labor, 2008). The wall system was designed using ProEngineer and then modeled in ANSYS Explicit Dynamics and AutoDYN. The system designed is a general single-degree-of-freedom design that is 20 feet long and 6 feet tall which covers a majority of the underground coal mines in Kentucky. By using single-degree-of-freedom analysis, the wall width can theoretically stretch to infinity. Therefore, the only dimension which affects the performance is the height. Once a successful wall was designed for a typical coal mine height, only minor modifications were necessary for taller or shorter walls. The supporting steel frame systems considered for the design were Solid Square, Hollow Square and Rectangular tube, and W sections or I-beams. All support system elements were structural steel with an ultimate strength of 60 KSI. These supports are held in place by C shapes, or steel channels, on the top and bottom of the system which are bolted to roof and floor of the mine. The polycarbonate panels are bolted to the supports on the outby side of the frame. The supports are spaced no closer than 30 inches per MSHA code for minimum support spacing as to allow a stretcher to be passed through the door panel (Department of Labor, 2008).

The initial design was developed in ProEngineer and used eight Solid Square 5in x 5in supports consisting of six vertical pieces spaced on 48 inch centers and two horizontal pieces spaced at 72 inches. Polycarbonate panels one inch thick and 48 inch wide were then fastened to the outby side of the supports. Figure 1 shows the initial design with Solid Square 5in x 5in supports and one inch polycarbonate panels.

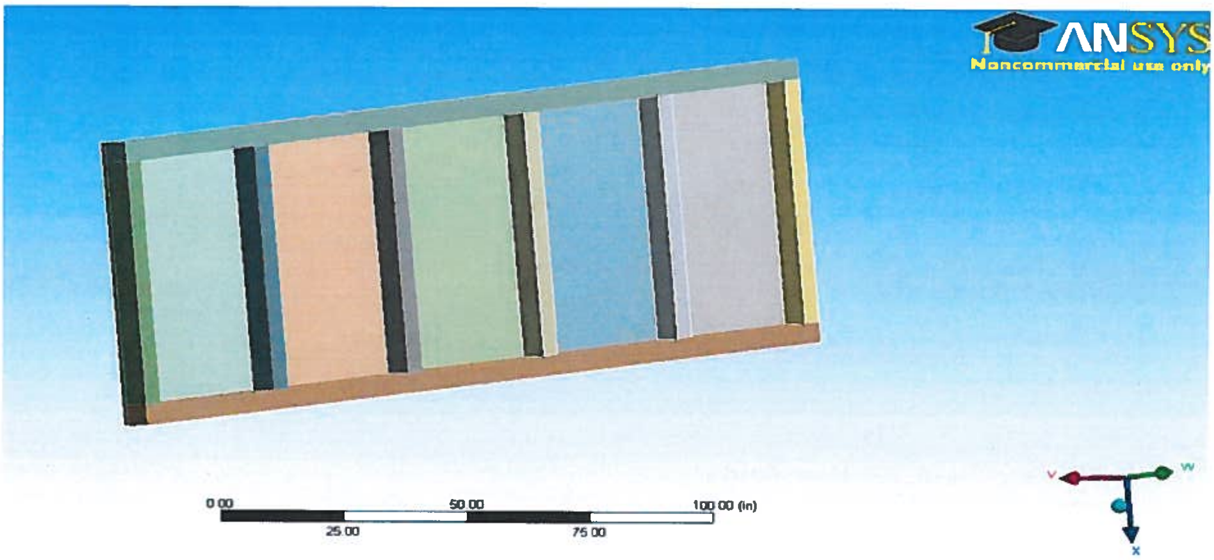

Figure 1 - Initial Design with Solid Square 5in x 5in Supports and 1" Polycarbonate Windows

The design was then imported into ANSYS Explicit Dynamics where it was given parameters and setup for modeling. All connections within the system were bonded within the program to simulate being bolted together. The top and bottom of the system were given fixed end-conditions to simulate being bolted into the ceiling and floor of a mine. The wall sides remained free as to force a one way reaction of the structure. The design was then subjected to 15 and 30 PSI loads over the 200 millisecond interval. The resulting deformations and stresses of the polycarbonate windows and steel frame are shown in Figures 2, 3, 4, and 5.

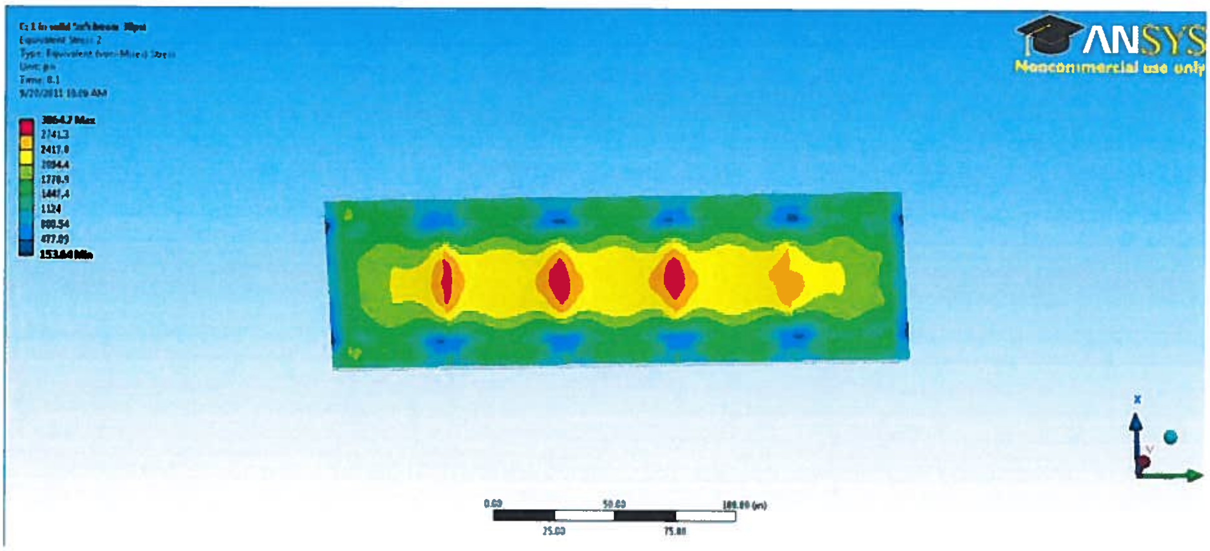

Figure 2 - Stresses in the Polycarbonate Windows

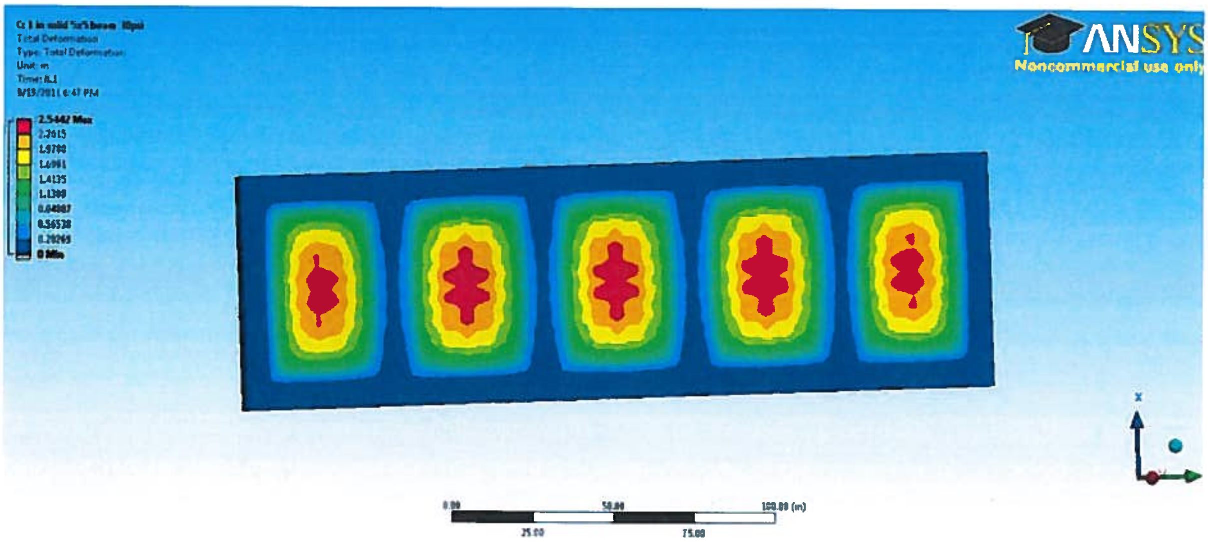

Figure 3 - Deformation in the Polycarbonate Windows

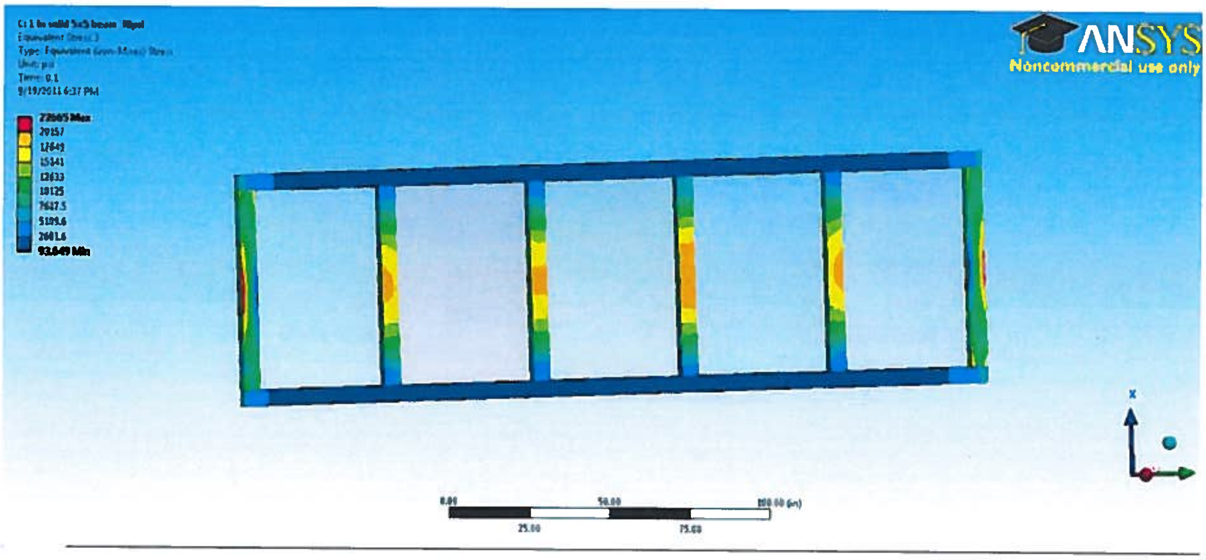

Figure 4 - Stresses in the Solid Square Steel Supports

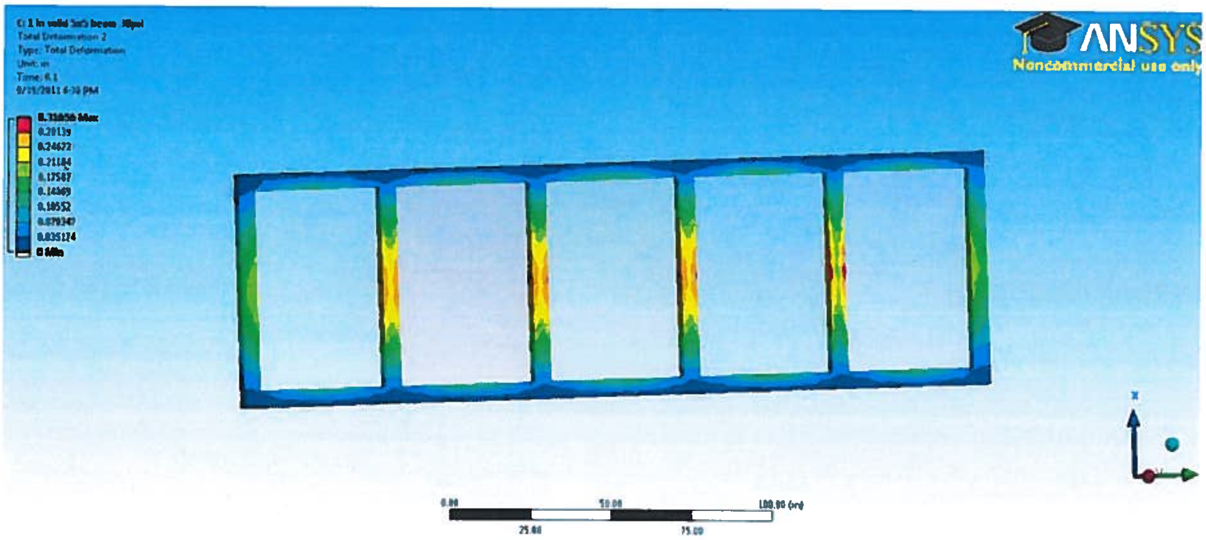

Figure 5 - Deformation in the Solid Square Steel Supports

Table 1. Results from Initial Design at 30 and 15 PSI

Model #	Poly Thickness (in)	Blast Pressure (psi)	Total Deformation Support (in)	Total Deformation Poly (in)	Total Stress Support (psi)	Total Stress Poly (psi)
1	1	30	0.31656	2.5442	22665	3064.7
2	1	15	0.16622	1.9275	13370	1843.5

After modeling completion for the initial design, it was apparent that the design was successful. The materials did not break and the ultimate strengths of the materials were not exceeded. However, one of the goals of the wall was to be easily constructed. With the Solid Square 5 inches x 5 inches weighing over 400lb/ft, the design would not have met that goal. Therefore, the design was altered to use Hollow Square and Rectangular tube to reduce the weight of the supports so that they can be easily handled by a few workers. The new system designs used Hollow Rectangular tube (HSS) and I-beams starting around the initial design size fitted between a channel at the top and bottom of the system. Using a channel to hold the vertical support system together brought the challenge of finding the right combination of depth of support that could fit into the allowable depth of the desired channel. This was much more challenging when trying to design a system using I-beams as the vertical support because of the limited number of shapes commercially available. These systems were based on 48 inch centers for the supports and polycarbonate windows with thicknesses of 1 to 2 inches and were subjected to a 30 PSI blast in 200 milliseconds. For the most part the designs did not fail, however the stresses in the supports exceeded the 60 KSI ultimate strength of the steel.

In attempt to distribute the large stresses the supports need to resist, the spacing between the vertical I-beam and HSS supports was reduced to the minimum allowable of 30 inches and the polycarbonate windows thickness was increased to 3 inches. In response, the stresses were reduced but they were still greater than the allowable stress for the steel in the supports. In an attempt to further improve the resistance, the supports were increased in size. This reduced the stress and gave results close to the allowable stress for the steel. However, the supports are still bulky and not meeting the goal of an easily constructed design. Furthermore, the designs using I-beams for supports resisted the stresses from the blast better than the HSS supports. Results for the reduced spacing at the 30 PSI pressure are shown in Table 2 below.

Table 2. ANSYS Modeling Results

Run	Channel	Support	Material	Poly Thickness (in)	Spacing (in)	Total Deformation Support (in)	Total Deformation Poly (in)	Total Stress Support (psi)	Total Stress Poly (psi)
3	MC 7x22.7	HSS 6x6x0.625	struc steel	2	30	4.585 piece broke	2.4946	111020	11771
4	C 12x30	HSS 6x4x0.375	struc steel	3	30	11.651 broke	2.4158	99841	12394
5	MC 4x13.8	HSS 6x4x0.5	struc steel	2	30	0.808	2.2927	493550	11709
6	C 12x30	HSS 7x4x0.5	struc steel	3	30	8.1231	1.9472	100125	12272
7	MC 4x13.8	HSS 8x4x0.5	struc steel	2	30	3.3451	1.5013	391270	13917
8	C 15x50	HSS 12.5x13.75x0.625	struc steel	2	30	7.5321	1.5707	92119	11645
9	MC 12x50	W 10x77	struc steel	2	30	1.0806	1.4569	86866	6095.6
10	C15x50	W 12x152	struc steel	3	33	0.67482	1.6926	80938	10628
11	C 15x50	W 12x152	struc steel	2	33	10.923 broke	1.8621	100075	7428.1
12	C15x50	W12x152	struc steel	3	30	0.61711	1.5304	75144	6007
13	C 15x50	W 12x152	struc steel	2	30	1.2784	1.5931	77590	8098.3
14	MC 18x58	W 14x283	struc steel	3	30	10.991 broke	1.228	100023	9503

To further reduce the weight of the steel supports, hollow structural sections were substituted into the design. A successful design was eventually achieved to withstand the MSHA prescribed blast pressure after several iterations. The design consists of 14 hollow structural sections 8"x4"x0.625" vertical supports held in place by a C10x30 channel at the top and bottom. Polycarbonate panels with a thickness of one inch are bolted on the outside of the frame to complete the design. Figure 6 shows the completed design from the outby side allowing one to see the double supports. In Figure 7, the red circle illustrates how the supports fit in the channel and how the polycarbonate is attached to the supports.

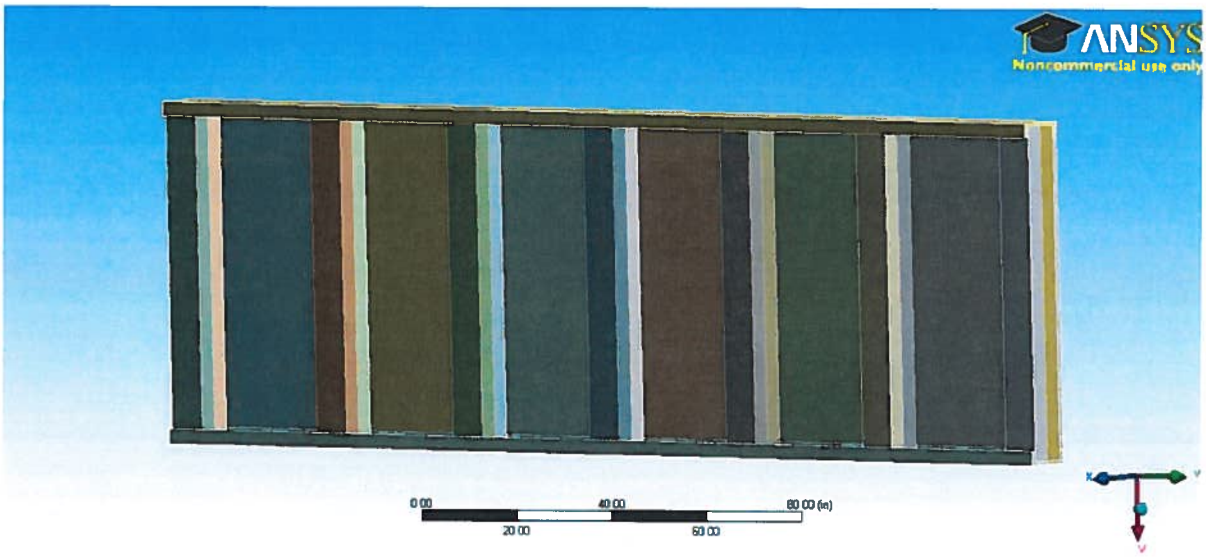

Figure 6 – Completed Successful Design

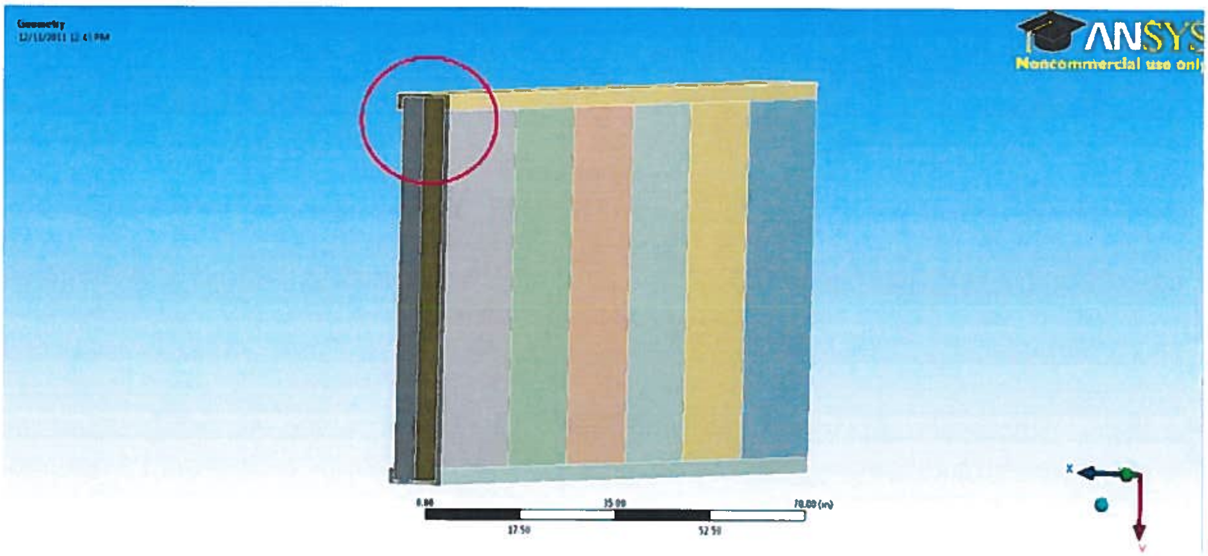

Figure 7 – Support Framing and Polycarbonate Interaction

The completed design was also altered from previous designs by adding an additional support directly behind each original support. Two supports were put back to back to allow for easier construction and greater distribution of the stresses incurred from the blast pressure. As a result, the design was able to successfully resist the required 30 PSI in 200 millisecond blast pressure when a safety factor of two is applied to the pressure. Figures 8, 9, 10, and 11 show the resulting deformations and stresses in the polycarbonate windows and steel supports.

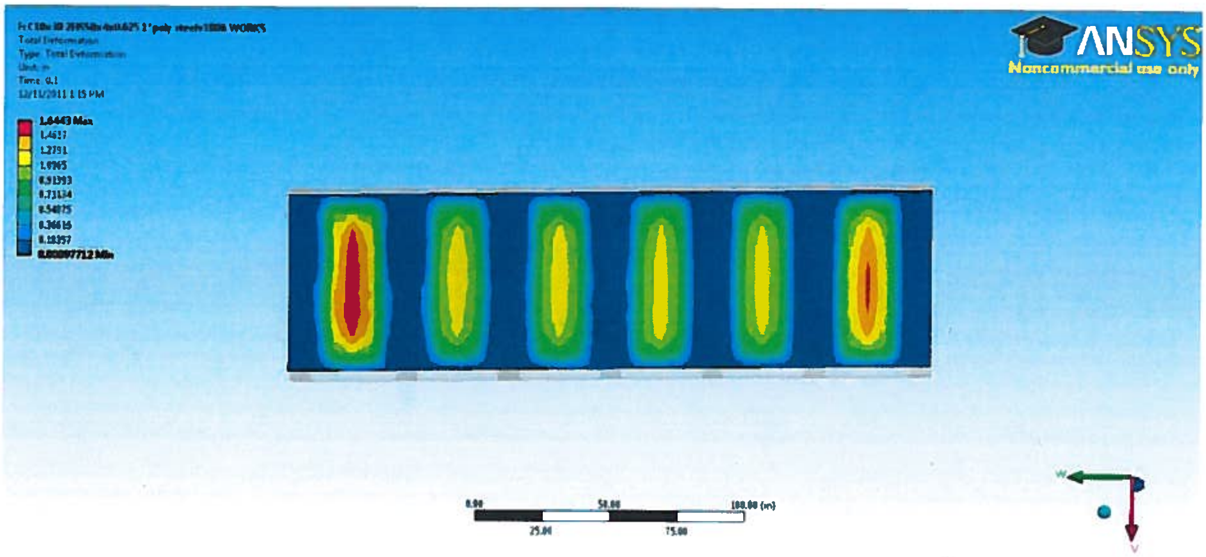

Figure 8 – Deformation in Polycarbonate Panels

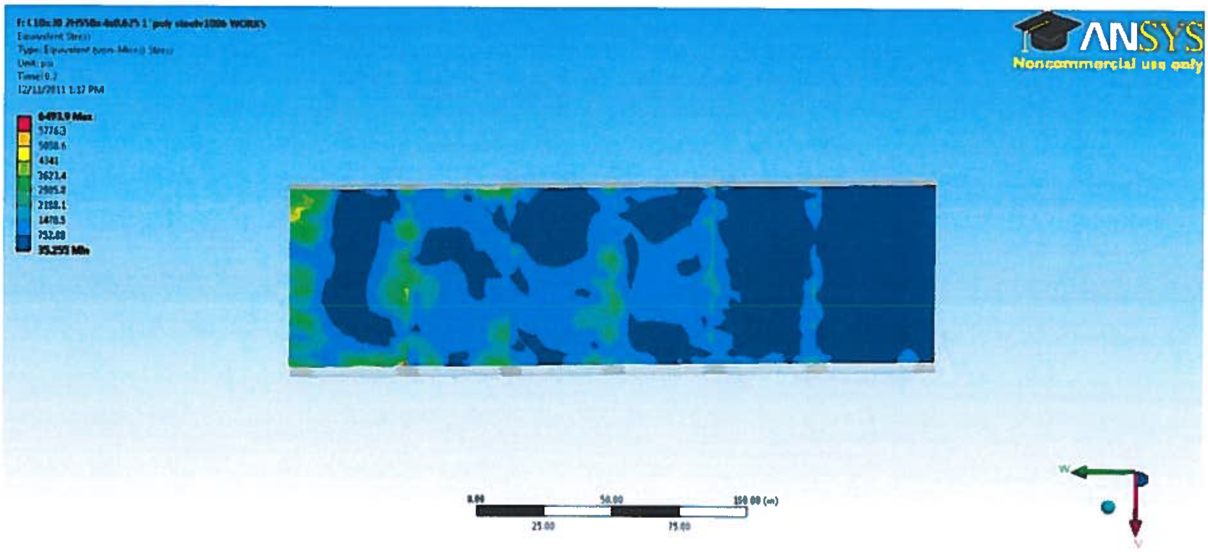

Figure 9 – Stresses in Polycarbonate Panels

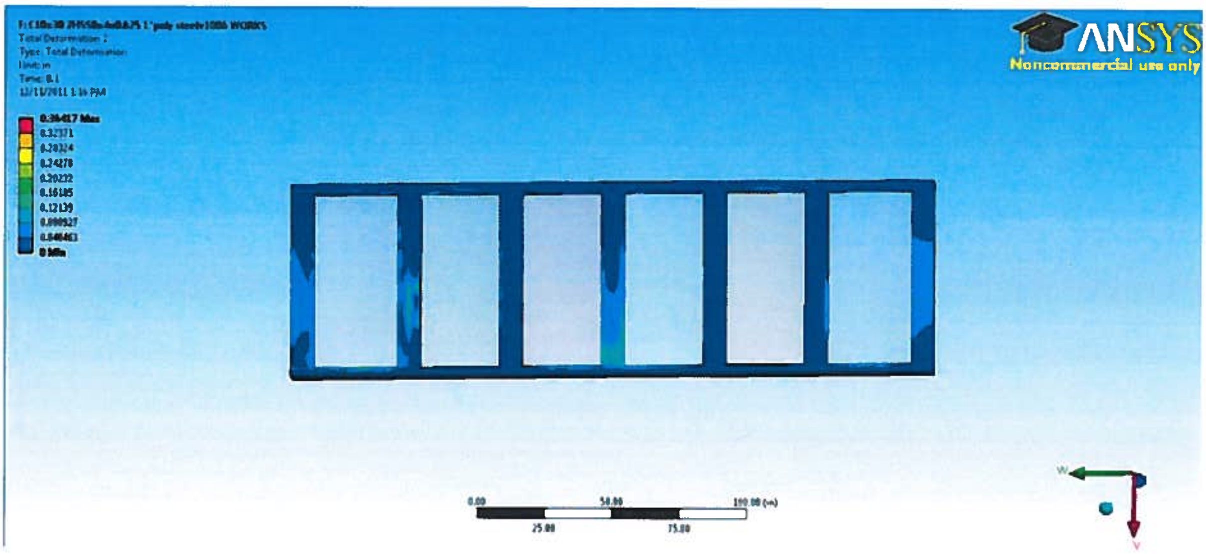

Figure 10 – Deformation in Steel Supports

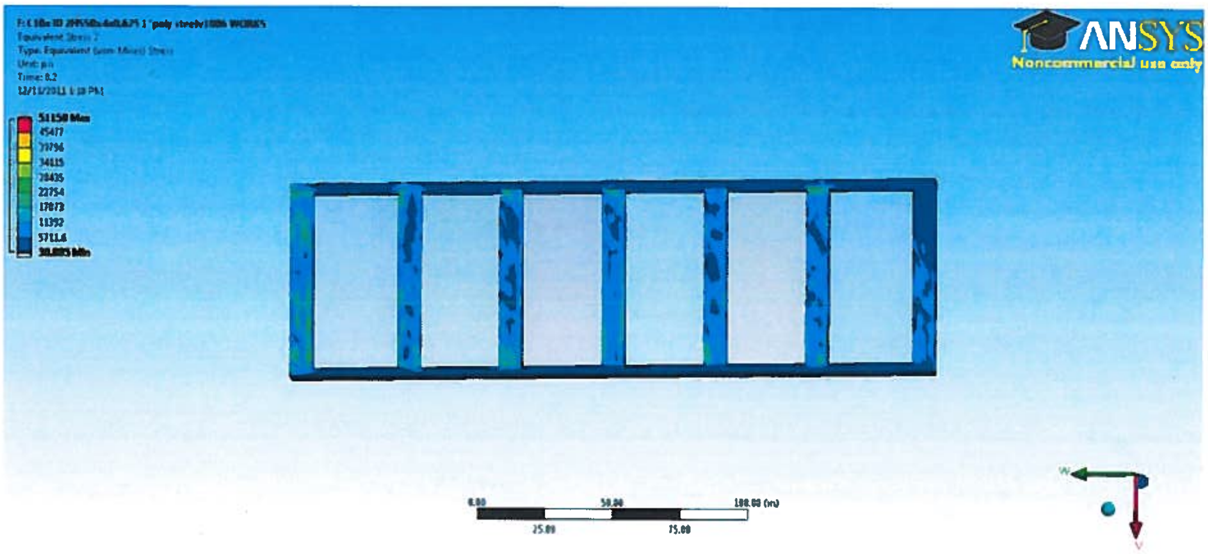

Figure 11 – Stresses in Steel Supports

The completed design meets the goal of being a lightweight and easily constructed safe haven wall system. The supports weigh roughly 42 pounds per foot; therefore, a six foot support weighs 252 pounds, which a two or three man crew can easily handle and build. Many designs were tested with double supports to optimize the design strength while still making the supports as lightweight as possible.

Once a successful design was achieved, the design was altered from its original six foot height to determine the maximum height at which the design would still be structurally sound. The design height was increased in one foot increments up to eight feet where the steel framing would no longer resist the blast pressure load. After the maximum height was determined, the polycarbonate thickness was minimized. Table 3 below shows the results of the double support design modeling. The highlighted lines are the design that was manufactured and tested against the 15 PSI over 200 milliseconds blast pressure.

Table 3 – Results from Design Process at 30 and 15 PSI

2 Supports												
Channel	Support	Material	Poly Dimensions (in)		Spacing (in)	Total Deformation Support (in)	Total Deformation Poly (in)	Total Stress Support (psi)	Total Stress Poly (psi)	Height (ft)	Pressure (psi)
C10x30	2 - HSS 8x4x0.625	struc steel	3	66x44, 66x38	30, 32	0.58994	1.3073	73789	5621	6	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	66x44, 66x38	30, 32	0.84884	1.3655	55077	7109	6	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	66x44, 66x38	30, 32	0.71477	1.2117	53812	6916.3	7	30
C10x30	2 - HSS 8x4x0.625	steel 1006	3	66x44, 66x38	30, 32	0.69669	1.7557	60132	6075.9	8	30
C10x30	2 - HSS 8x4x0.625	steel 1006	1	66x44, 66x38	30, 32	0.36417	1.6443	51158	6493.9	6	30
C10x30	2 - HSS 8x4x0.5	steel 1006	1	66x44, 66x38	30, 32	1.2247	1.9266	72907	13193	6	30
C10x30	2 - HSS 8x4x0.5	steel 1006	1	66x44, 66x38	30, 32	1.1291	1.6948	74223	14569	6	15
C10x30	2 - HSS 8x4x0.625	steel 1006	1	66x44, 66x38	30, 32	0.95851	1.17	57278	7547.2	6	15

Bolt Design

Once a successful wall design capable of resisting the blast load was achieved, a bolt pattern to fasten the whole design together was designed. The bolt pattern was design based on the shear failure of the bolts. The shear stress required to be resisted by the bolts was calculated by taking the peak shear stress at the edge of a polycarbonate panel under the required blast pressure. The shear stress produced by the blast load was calculated with ANSYS. Using the stress value and a known shear strength for a chosen bolt diameter, the total number of bolts required was determined. A total of 22, 11 per edge, 0.75 inch diameter grade 5 bolts were needed to withstand the shear stress generated in each polycarbonate panel. Three panels were used in the design for laboratory explosion testing, therefore, a total of 66 bolts were required to secure the polycarbonate to the steel frame. An additional 12 bolts were required to fasten the supports into the channel on the top and bottom of the design. The bolts that were used are 12 inches long, 0.75 inch diameter, and go through the two supports and channel on the top and bottom. Bolts used to fasten the polycarbonate panels to the steel frame are 10 inches long with a 0.75 inch diameter. Calculations and ANSYS results for the bolt design can be found in Appendix D.

Polycarbonate Wall Materials

With the design finished, the polycarbonate wall materials were procured. The steel for the framing system is standard A36 hollow structural sections and channels. The polycarbonate panels were secured from Makrolon. Other materials such as bolts, washers, and nuts for connection the polycarbonate to the steel were also purchased.

Polycarbonate Wall Construction and Testing

Polycarbonate Wall Construction

The next step in the project was construction and testing of the polycarbonate wall at the high explosive shock tube facility in Georgetown, Kentucky. The process started with reducing the cross-sectional area of the existing 10'x10' shock tube opening down to six foot high by 114 inches wide to simulate a six foot entry in a coal mine and keep explosive pressure from easily escaping the opening. The width was chosen as it allowed for exactly three equally sized polycarbonate panels to be installed. The size reduction was achieved by placing eleven 3.5"x12"x120" oak boards on top of an I-beam support as shown in Figure 12.

Figure 12 – I-beam and Oak Boards Size Adjustment Configuration

The I-beam was fastened horizontally through oak boards to the steel shock tube framing with bolts through angle pieces that also bolted to the web of the I-beam on both ends as shown in Figure 13. The I-beam was also supported vertically by oak boards on each end.

Figure 13 – I-beam Horizontally Bolted Through Oak Boards to Steel Shock Tube Frame with Steel Angle

Once the I-beam and oak board size adjustment was in place, 5/8" threaded steel bars were inserted from the top of the shock tube frame down through holes previously drilled in the oak boards and I-beam to further anchor the cross-sectional size adjustment together. Figure 14 shows the completed size adjustment with threaded steel bars inserted to anchor the system together.

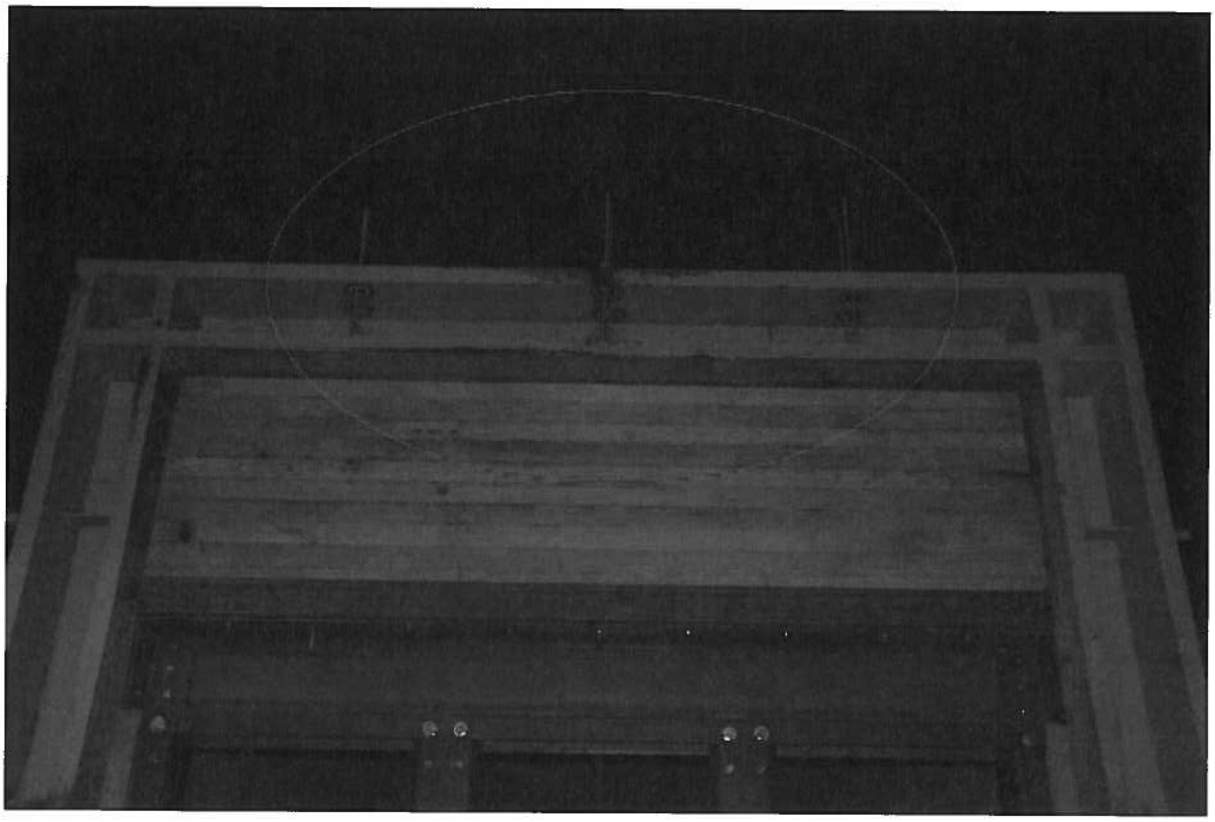

Figure 14 – 5/8" Threaded Steel Bars Through Boards and I-beam

With the shock tube opening to the required dimensions for the polycarbonate wall system, the steel frame was brought in to place and installed. The steel frame was drilled and assembled off-site to assure the steel and bolt holes would all align. Figures 15, 16, 17, and 18 show the installation progression. As with the models, the sides of the wall system remained free to force a one way reaction.

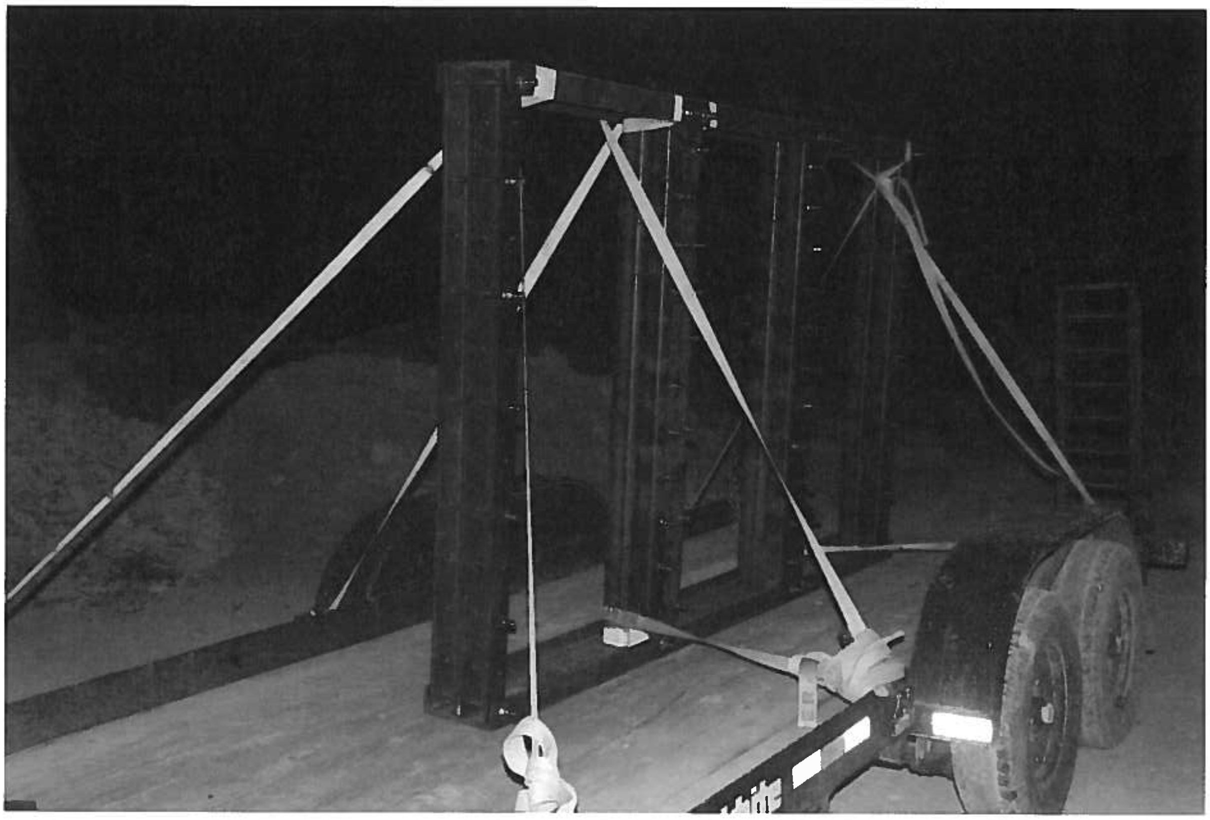

Figure 15 – Steel Framing Assembled Off-Site

Figure 16 – Steel Framing Final Placement for Bolting

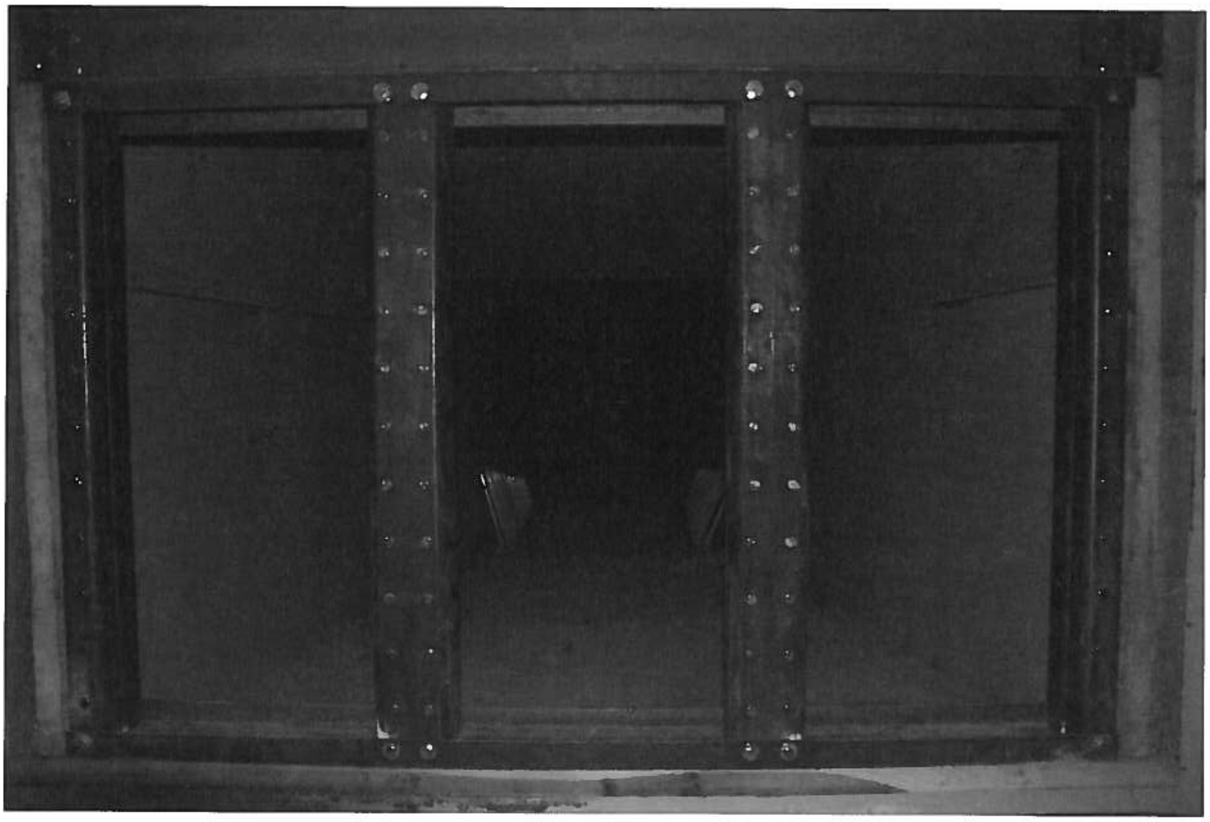

Figure 17 – Steel Framing Bolted in Place

Figure 18 – Bolt Pattern on Bottom Channel of Steel Frame

Following the installation of the steel framing, one inch polycarbonate panels were cut to the required 66"x38" dimensions to fit the frame. After the polycarbonate was cut to the proper dimension, it was placed against the steel framing to mark the as-built holes in the steel framing system. The panels were then removed and holes were drilled where marked. The middle panel was marked first followed by the left and right side to ensure that any gaps between the polycarbonate was on the outside of the system. Figures 19, 20, and 21 show the installation of the polycarbonate panels.

Figure 19 – Middle Polycarbonate Panel Installation

Figure 20 – Bolt Hole Drilled in Polycarbonate Panel

Figure 21 – All Polycarbonate Panels Installed

The final step in the construction of the system was placing steel plates on the perimeter of the oak board size adjustments to add extra support against their movement and to further help seal off any opening where explosive pressure may be lost. The 0.25 inch thick steel plates were simply drilled and fastened to the oak boards using 2.25 inch long, 0.25 in diameter anchors. With the steel plates in place, the wall installation was complete and ready for testing. The steel plate's placement can be seen in Figures 22, 23, and 24.

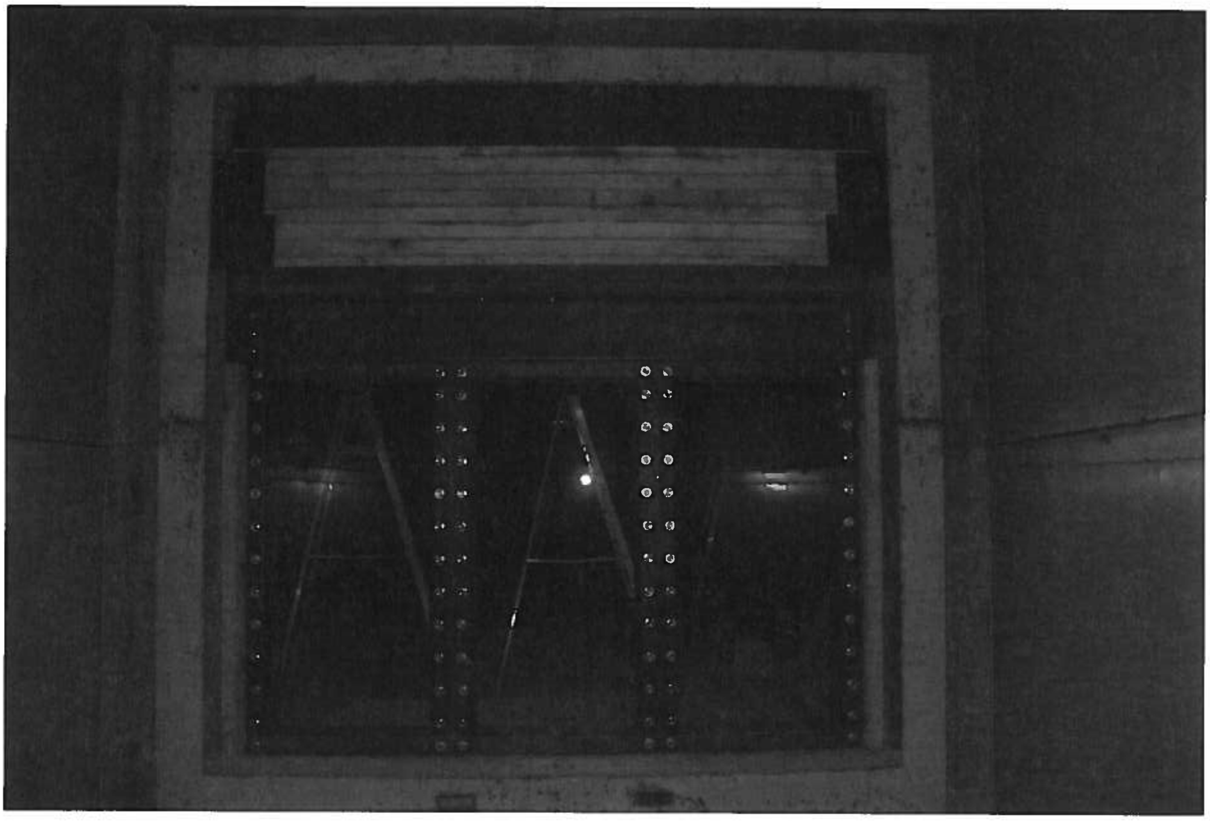

Figure 22 – Steel Plate Placement on Inby Side of System

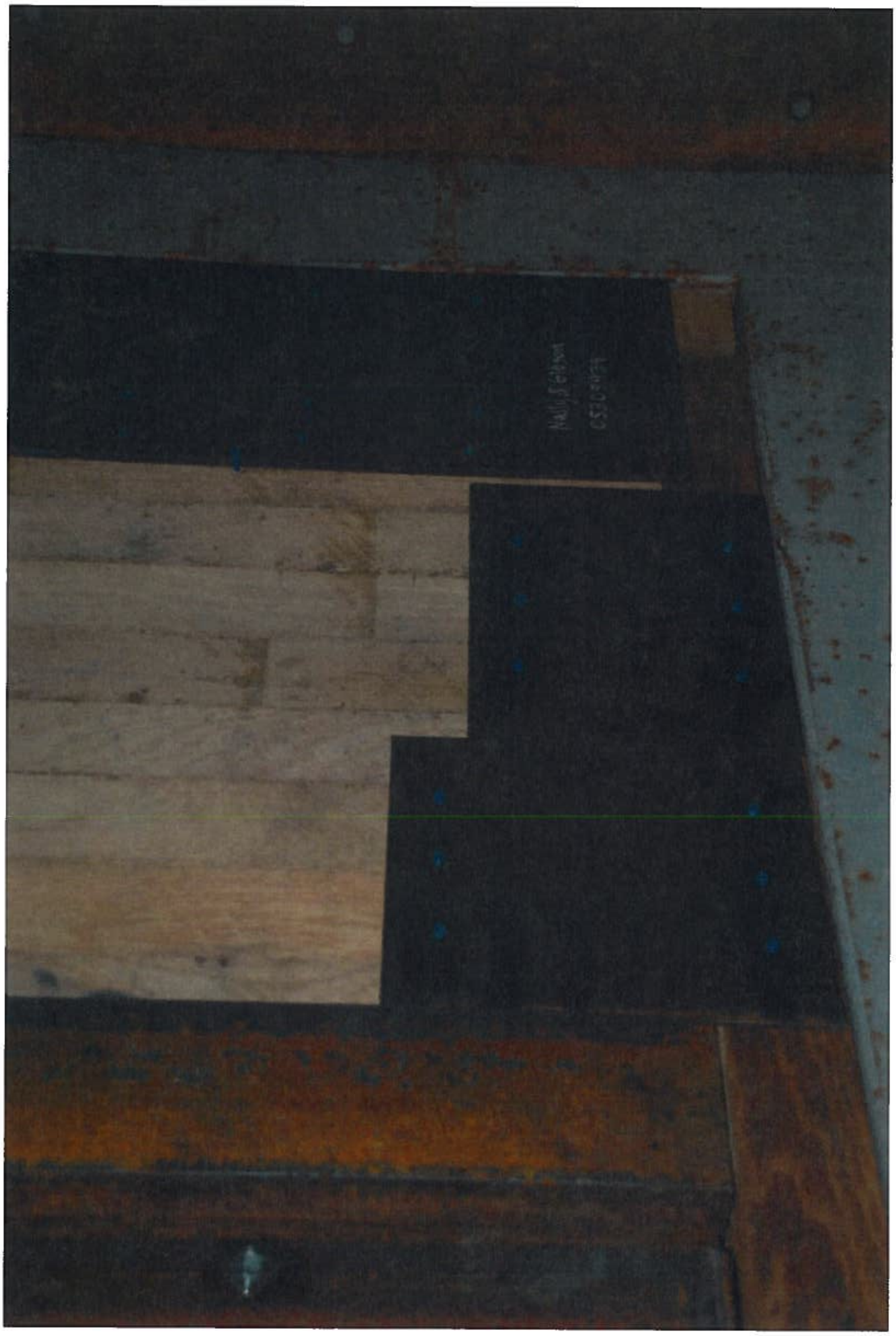

Figure 23 – Steel Plate Placement

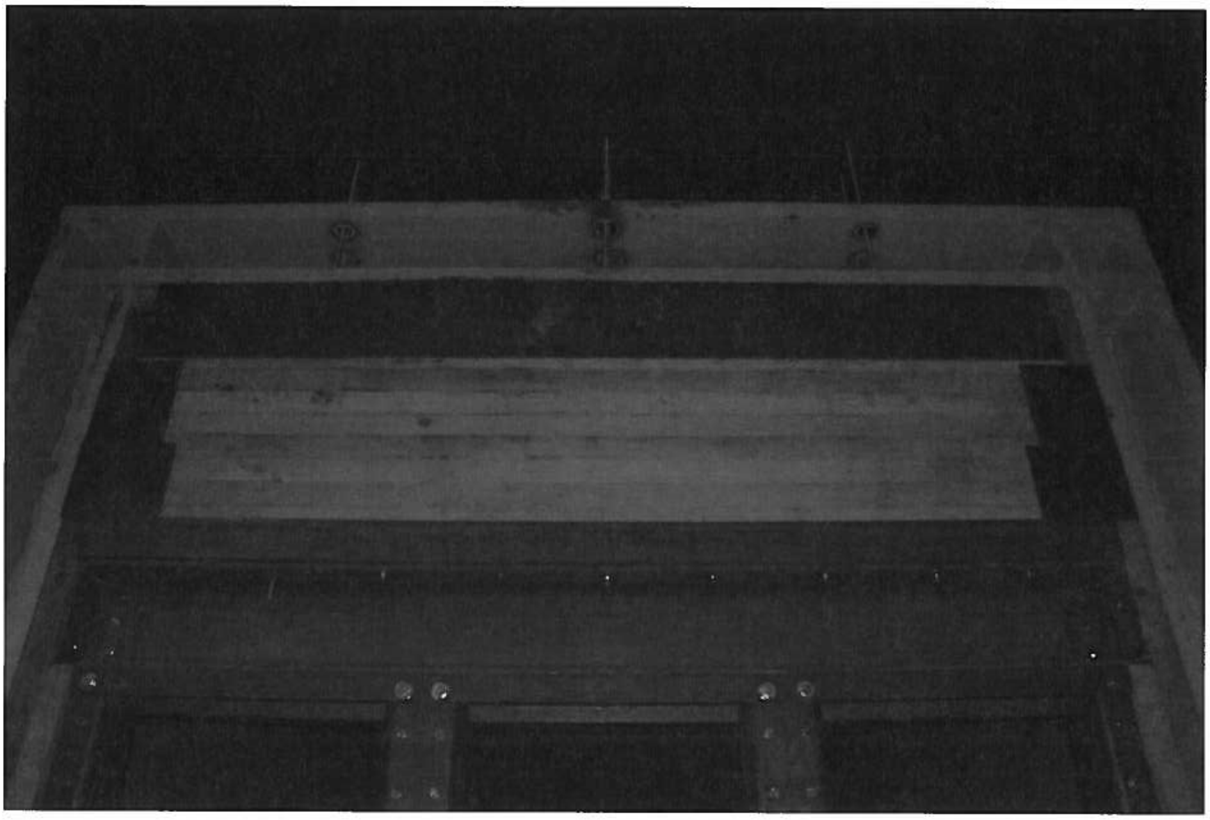

Figure 24 – Steel Plate Placement on Outby Side of System

Polycarbonate Wall Testing

With the polycarbonate safe haven wall installed, the next step was to test system. The testing setup consisted of three pressure sensors located as shown in Figure 25 to record explosive pressures being experienced by the wall system and a displacement laser to record the deflections of the steel framing and polycarbonate panels. Four tests were performed to record deflections on the center polycarbonate panel, left-center vertical support, far left half support, and the left polycarbonate panel. The deflections of the right side were assumed to be same as the left due to symmetry. The laser was moved for each test to record the deflections and the pressure sensors also recorded pressure for each test. Each test was also captured with standard and high speed video to document and identify any movement or significant action that occurs during the blast test. Figure 26 shows one frame from a high speed video along with the laser being used to measure deflection. The pressure for each test was created by hanging a C4 charge 51 feet from the wall. This initial round of testing consisted of four tests.

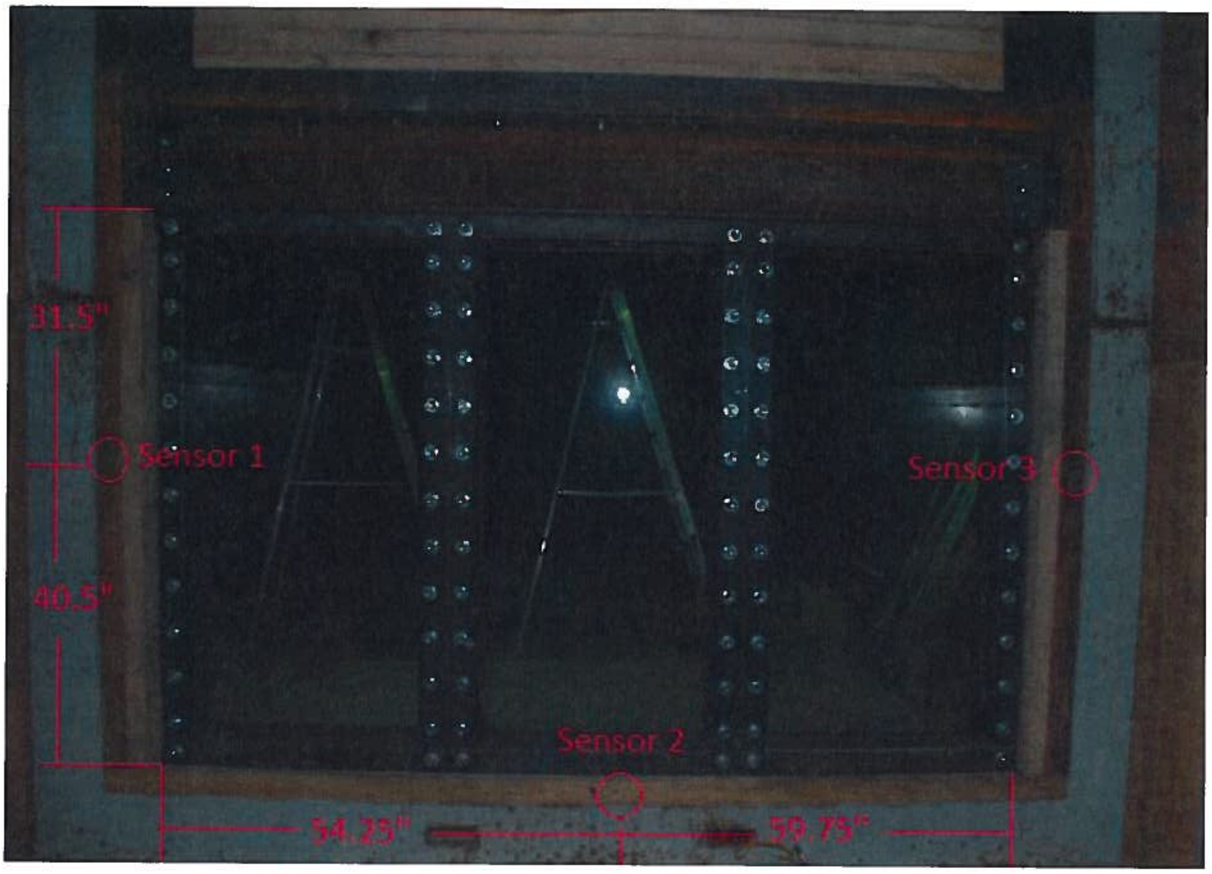

Figure 25 – Pressure Sensor Locations for Testing

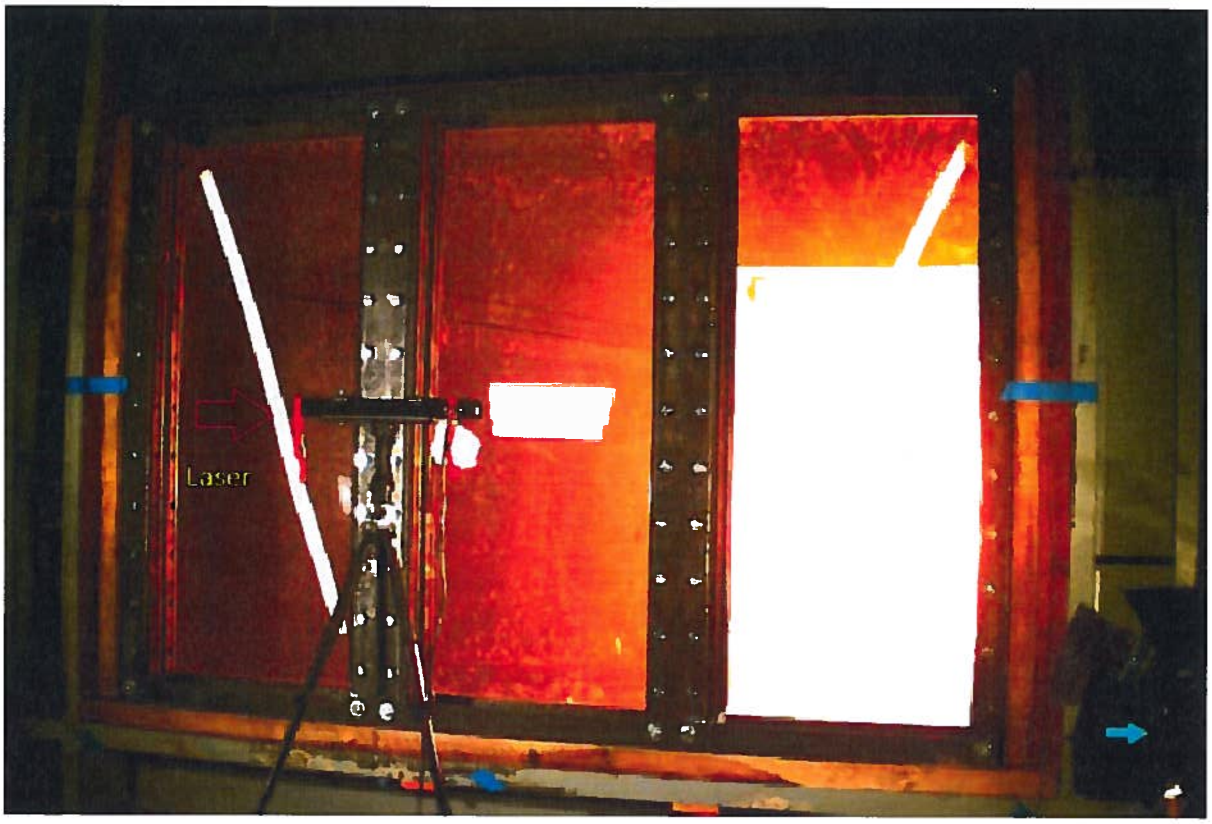

Figure 26 – High Speed Video Screen Shot and Displacement Laser

Testing Results

The system faired very well against the blast pressures that it was subjected to in the tests. The pressures and impulses for each test and each sensor were recorded and then averaged to create one pressure versus time waveform for each test. Each averaged pressure waveform was imported into ANSYS Explicit Dynamics and AutoDYN and modeled against the system design to determine the deflection of each part that was measured during testing. The resulting deflections from the model and actual test can be seen in Table 4.

Table 4 – Deflection Results from Model and Actual Test

Test Number	ANSYS Deflection (in)	Testing Deflection (in)	Average Pressure (psi)	Average Impulse (psi-ms)	Laser Location
*03161202	1.22	0.907485	7.61	70.41	Center of middle polycarbonate panel
*03161203	0.33354	0.73311	7.6	69.73	Center of left-center vertical support
*03161204	0.5075	0.906855	7.69	71.57	Center of far left vertical support
*03161205	1.9512	1.03918	7.61	69.11	Center of left polycarbonate panel

From the results in Table 4, the deflections vary from as little as 0.33 inches to 1.95 inches. The deflections from the model were greater on the polycarbonate panel and less on the vertical steel supports. This may be due to pivoting at the polycarbonate wall system and I-beam connection. The pivoting allows the steel frame to move more than it would if it was directly fastened the roof of a mine, thus resulting in a greater deflection. Since the model does not allow this pivot due to the top and bottom being fixed, the deflection of the steel is less. As for the polycarbonate panels, the deflection in the models were greater than that found through testing. The polycarbonate material being used for the system is a relatively new material and does not have a material model within the software. However, information has been obtained by the manufacturer and a material model is currently under development but was not able to be completed by the end of the project. Newer technology has allowed the Makrolon Hygard polycarbonate to be stiffer than the standard polycarbonate material model within ANSYS and deflections were expected to be smaller from testing than modeling. A further comparison of the deflections measured by the blast testing and ANSYS can be found in Appendix E.

The results show that the required pressure for testing the design and MSHA approval was not met. While reaching the peak pressure is not a problem within the shock tube, creating the prescribed waveform presents a difficult challenge. Several small scale tests of a new explosive material and detonation system were performed. While the pressures were lower than that of the C4 (approximately 4 PSI), the waveform duration was longer and showed promising results. However, damage to the shock tube did not allow for further investigation during this test series. Therefore, development, implementation, and the ability to replicate the same charge size every time of this system to a full scale experiment is currently being researched.

Model for Underground Coal Mine Environment

While investigating a better way to physically test the system with explosives, a model for use in an underground coal mine environment using FLAC^{3D} was developed. The first step was to determine a suitable underground coal mine willing to support the projects goals. With a mine site selected, core hole data from the mine was gathered in order to determine the depths and thicknesses of stratums for modeling. Next, the dimensions of the model base had to be selected very carefully to allow for adequate modeling of the underground environment and timely conversion of the model. Multiple model base configurations were conducted before achieving the optimal parameters. The optimum model design layout comprised of a two entry section with one crosscut where the polycarbonate wall would be placed. However, to allow for faster conversion of the model, the layout was reduced to include only half of the pillars. Figures 27 and 28 provide drawings of the final layout used in the FLAC^{3D} model.

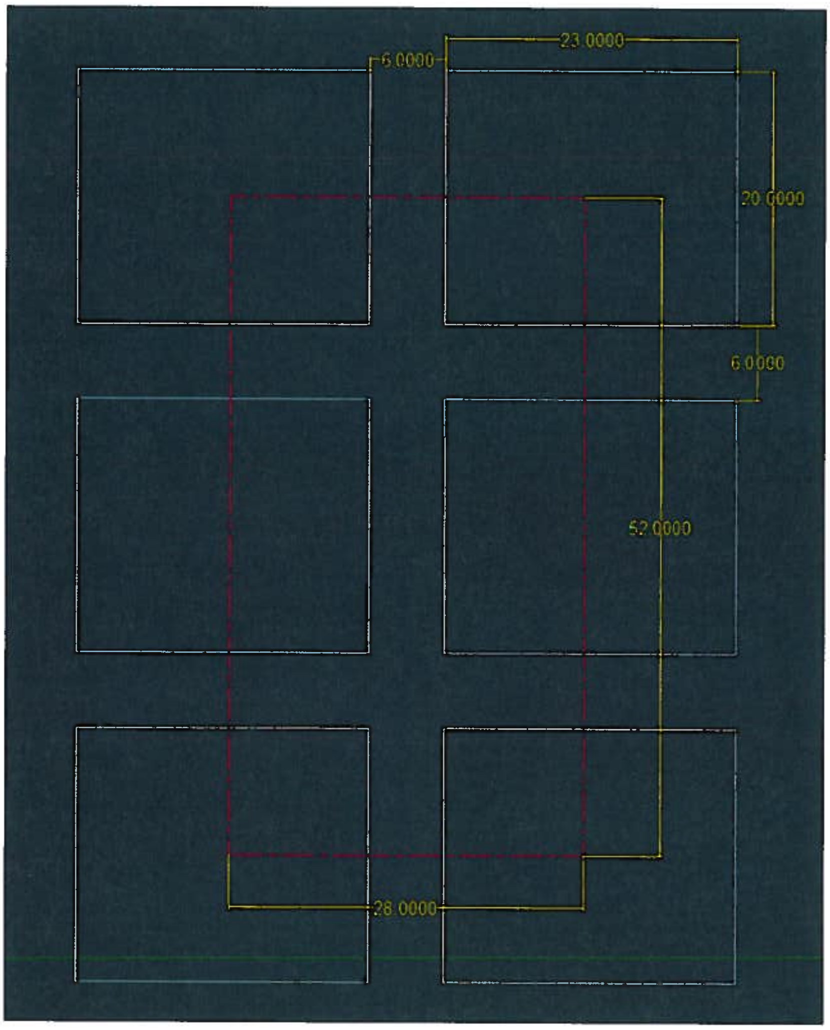

Figure 27 – Two Entry, One Crosscut Proposed FLAC3D Model (dimensions in meters)

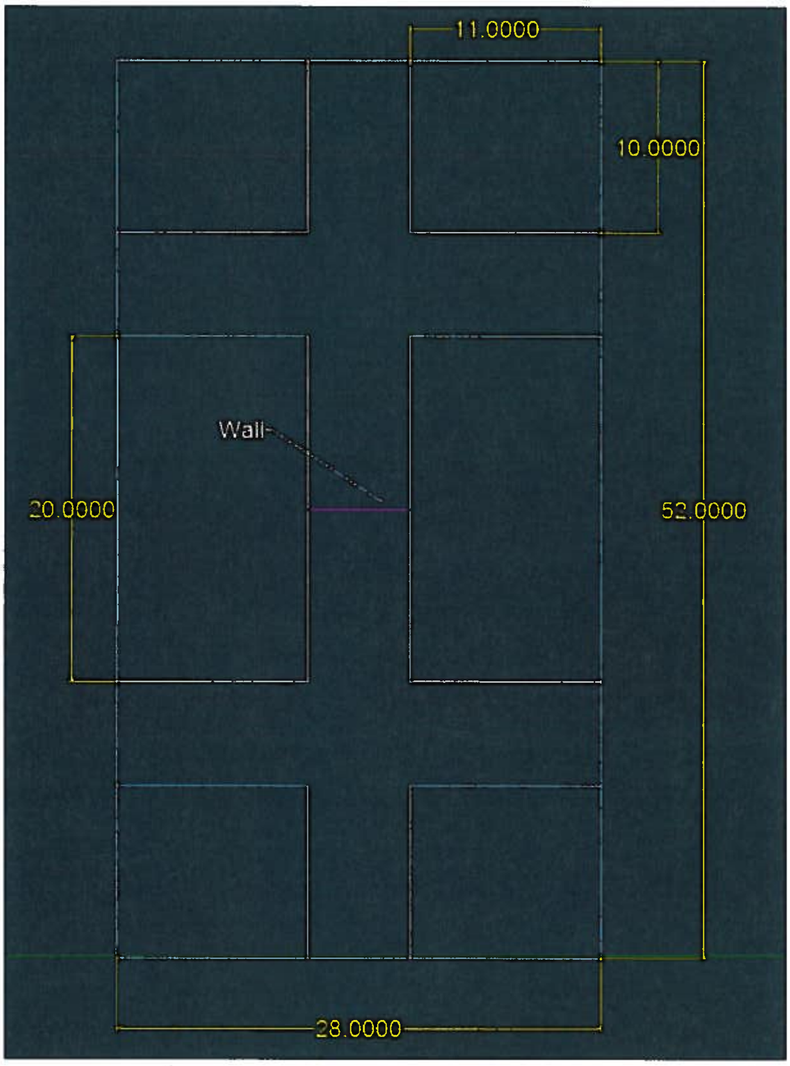

Figure 28 – Final FLAC3D Model Setup (dimensions in meters)

The model consisted of five layers, a gray sandstone and dark gray shale above and below a coal seam. For modeling purposes, stratums lying above and below the modeled area were allocated differently. The remaining stratums below the modeled area are deemed irrelevant while the remaining stratums above the modeled area will be realized by applying a 1.79e6 Pascal (~260 PSI) vertical stress to the top of the model. With the model base dimensions and layers established, required model parameters were coded to create the base model and allow for conversion. Table 5 below provides the dimensions for each stratum along with the values used for the required modeling parameters.

Table 5 – Strata Parameters Used for FLAC3D Modeling

Strata Parameters														
	x	y	z		E		v	Density		Tensile		ϕ	Cohesion	
Overburden														
Gray sandstone	170.6	91.84	9.84	ft	2800000	psi	0.18	165	lb/ft3	4833	psi	37	3916	psi
	52	28	3	m	1.90E+10	Pa		2640	kg/m3	3.33E+07	Pa		2.70E+07	Pa
zones	52	28	3											
Dark Gray Shale	170.6	91.84	9.84	ft	1740000	psi	0.27	150	lb/ft3	950	psi	30	5511	psi
	52	28	3	m	1.20E+10	Pa		2400	kg/m3	6.55E+06	Pa		3.80E+07	Pa
zones	104	56	15											
Coal														
Coal	170.6	91.84	6.56	ft	666000	psi	0.38	80	lb/ft3	962	psi	28	325	psi
	52	28	2	m	4.60E+09	Pa		1280	kg/m3	6.63E+06	Pa		2.24E+06	Pa
zones	104	56	10											
Floor														
Dark Gray Shale	170.6	91.84	9.84	ft	1130250	psi	0.27	150	lb/ft3	870	psi	30	5511	psi
	52	28	3	m	7.80E+09	Pa		2400	kg/m3	5.99E+06	Pa		3.80E+07	Pa
zones	104	56	15											
Gray Sandstone	170.6	91.84	6.56	ft	2650000	psi	0.18	165	lb/ft3	4833	psi	37	3916	psi
	52	28	2	m	1.80E+10	Pa		2640	kg/m3	3.33E+07	Pa		2.70E+07	Pa
zones	52	28	2											

Once the base of the model converged, excavation and bolting of the entries and crosscuts took place. Both the entries and crosscuts are six meters wide (~20 feet). For roof support, five three meter long bolts were installed on one meter centers throughout the excavation for roof support. Upon completion of the excavation and bolt installation, the model was again allowed to converge to tabulate stresses in the bolts due to gravity. Table 6 provides the properties used for the bolts and Figures 29-32 show the completed excavation with bolts installed and stresses in the bolts.

Table 6 – Bolt Properties Used in FLAC3D

Bolt Properties				
Area	0.0085	m^2	0.0914	ft^2
Youngs Modulus	2.00E+11	Pa	2.9E+07	psi
Tensile Yield Strength	1.00E+10	N	2.2E+09	lb
Grout Stiffness	7.00E+06	Pa	1015	psi
Grout Cohesive Strength	100	N/m	6.85	lb/ft
Grout Friction Angle	30	degrees	30	degrees
Grout Exposed Perimeter	0.16	m	0.5248	ft

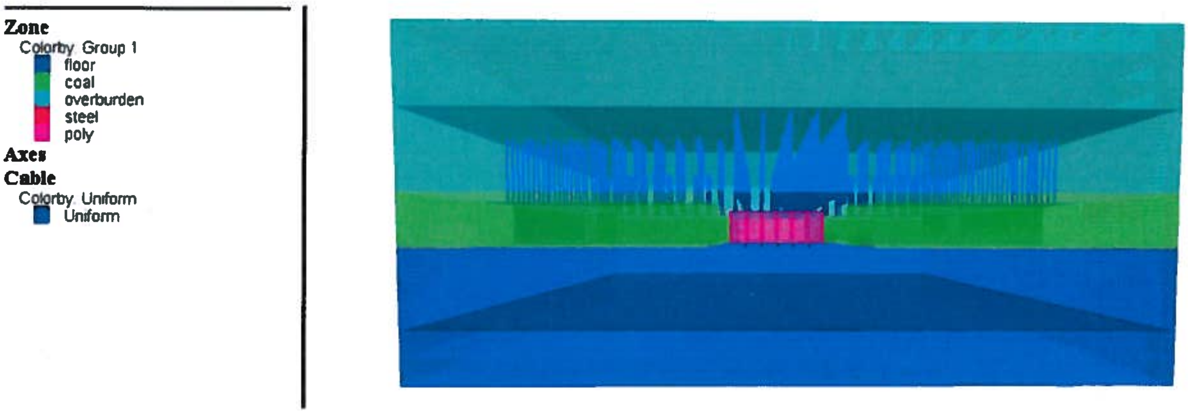

Figure 29 – Plot of Completed Model, Zones Depicted by Different Colors

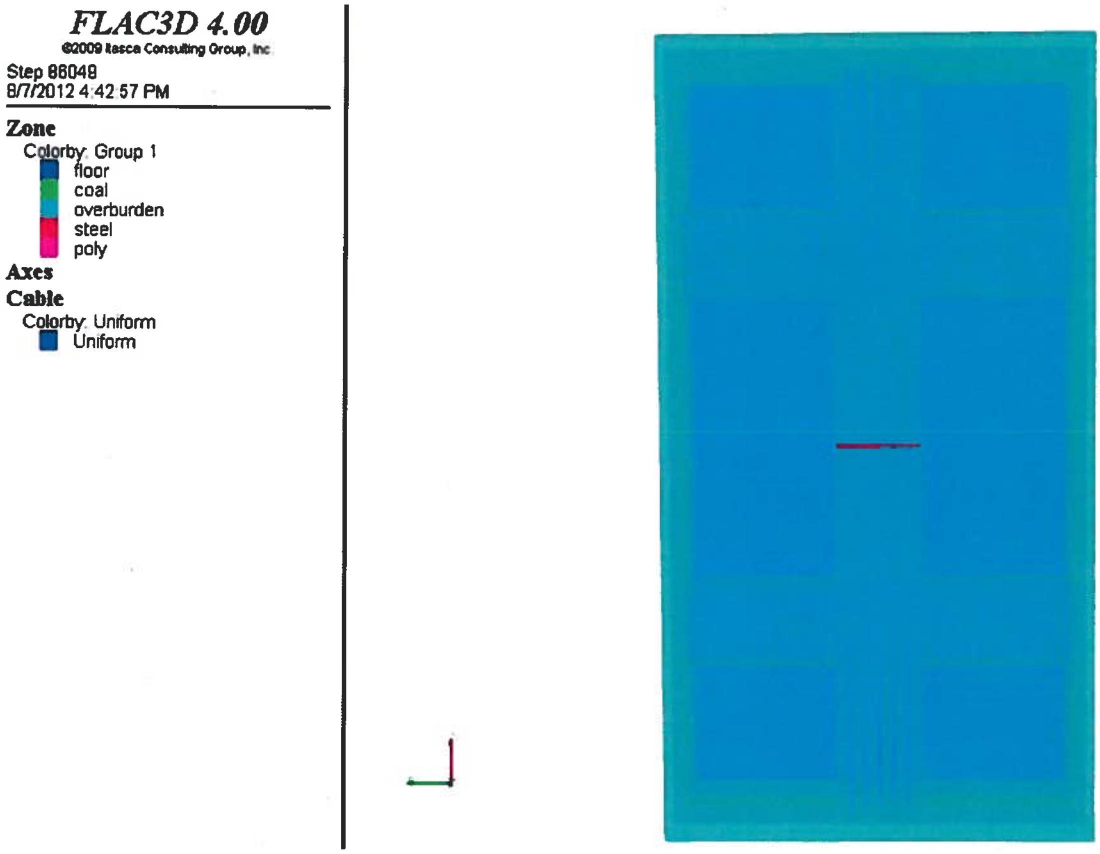

Figure 30 – Top View of Completed Model

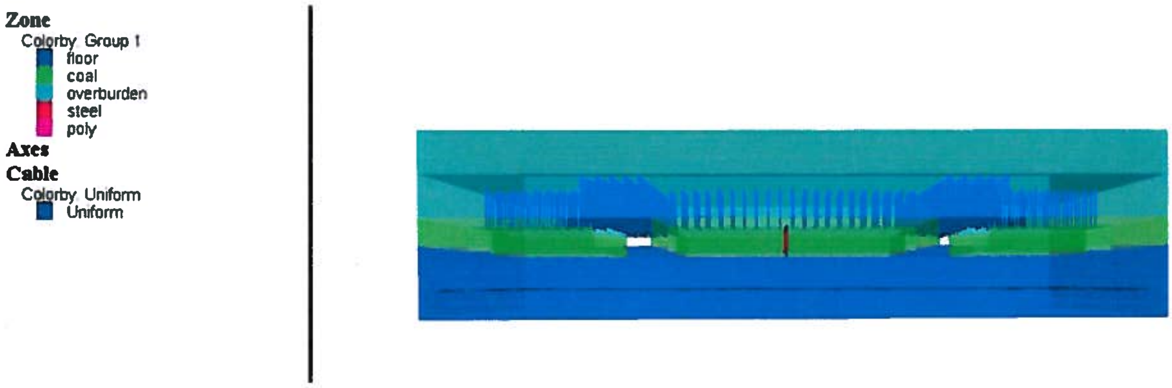

Figure 31 – Side View of Completed Model

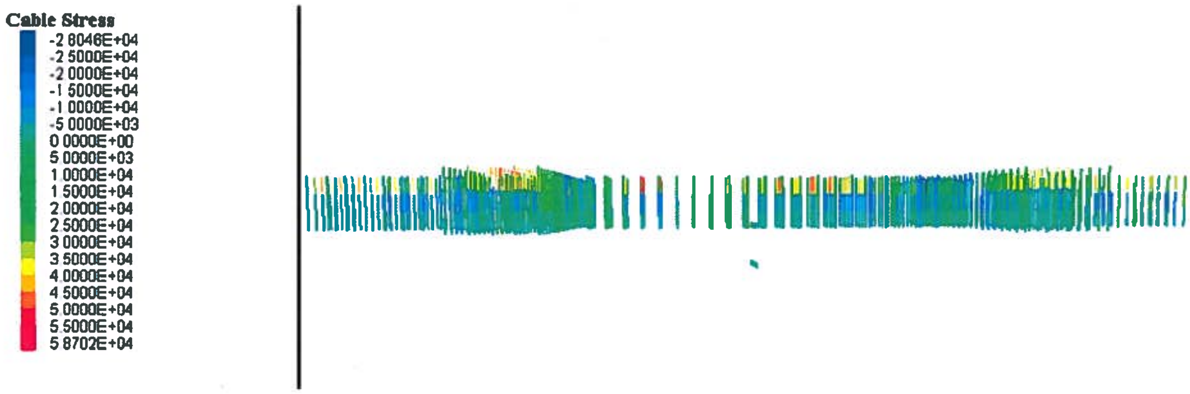

Figure 32 – Plot of the Stress in the Bolts

With the model to the current state of equilibrium, the polycarbonate wall system was placed in the crosscut as shown in previous figures. The polycarbonate wall was anchored to the floor and ceiling with 0.3 meter bolts in anticipation of similar bolts being readily available for the underground installation. These bolts have the same parameters as the bolts used before during the excavation stage of the modeling. All of the dimensions of the wall are the same as the successful design in the earlier section of this report. The parameters of the steel and polycarbonate used for the wall in the model can be seen in Table 7.

Table 7 – Polycarbonate Wall Parameters Used In FLAC3D

Polycarbonate Wall Parameters					
E		v	Density		
Steel					
29007547	psi	0.3	490	lb/ft3	
2.00E+11	Pa		7850	kg/m3	
Polycarbonate					
310380	psi	0.37	75	lb/ft3	
2.14E+09	Pa		1200	kg/m3	

The final step in the modeling process was to apply the prescribed blast pressure to the polycarbonate wall system. A 206,843 Pascal (30 PSI) pressure was applied to the wall and the model was allowed to converge for the final time. By applying pressure to the wall, the model was able to tabulate results for stresses and deflections in the polycarbonate wall. Figures 33 – 42 show the front and back view of the stresses and deflections that were developed in the polycarbonate wall from the applied pressure and gravitational forces of the model.

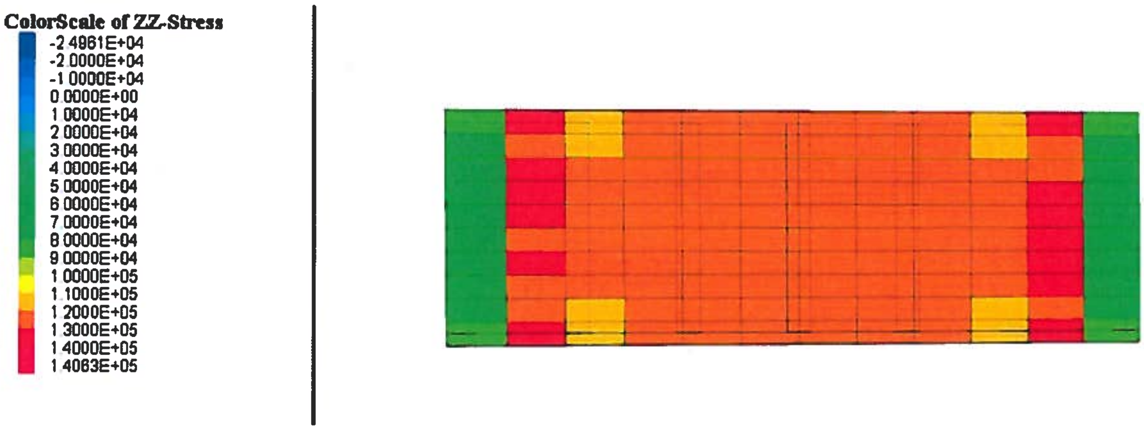

Figure 33 – Front View of the ZZ-Stress in the Polycarbonate Wall

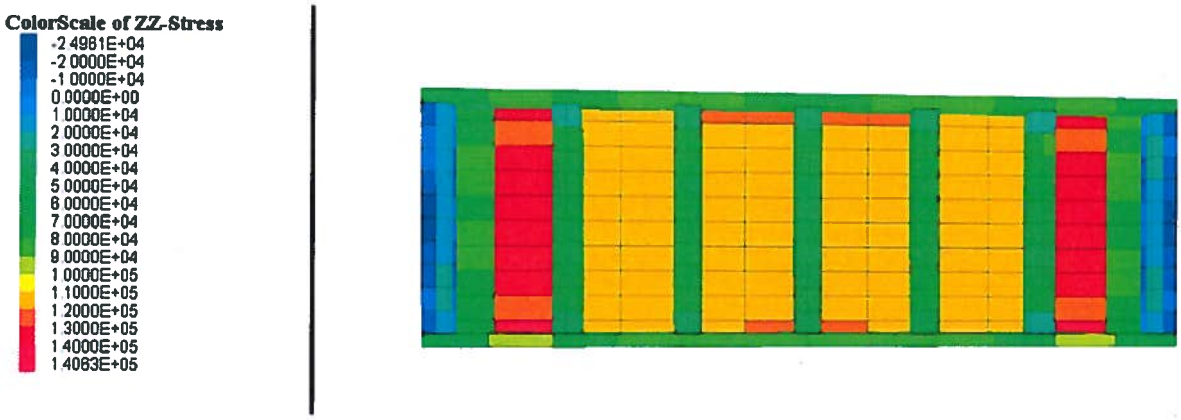

Figure 34 – Back View of the ZZ-Stress in the Polycarbonate Wall

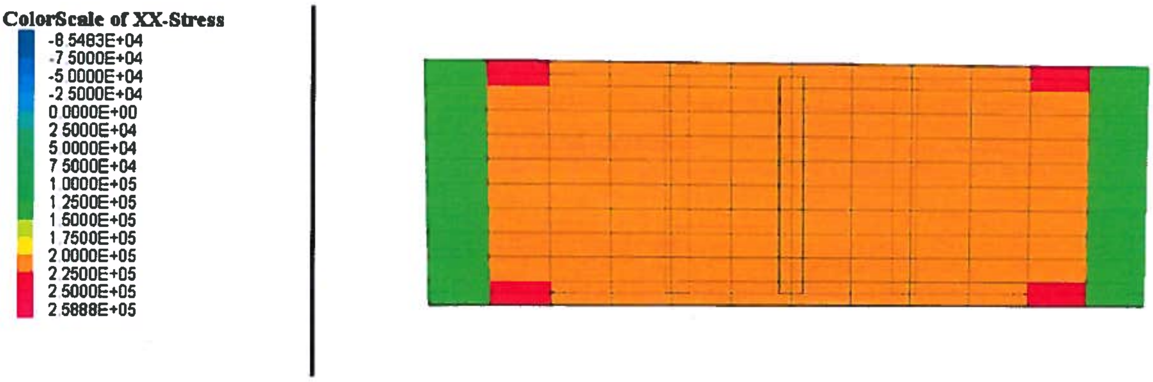

Figure 35 – Front View of the XX-Stress in the Polycarbonate Wall

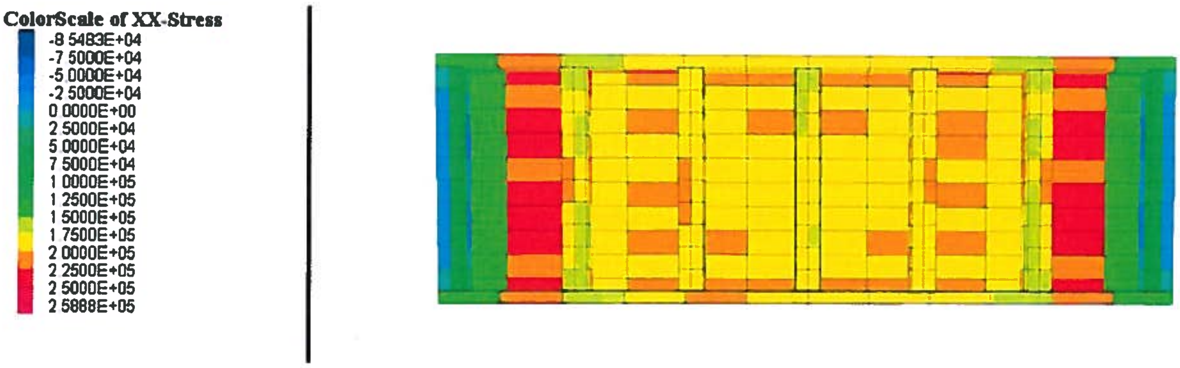

Figure 36 – Back View of the XX-Stress in the Polycarbonate Wall

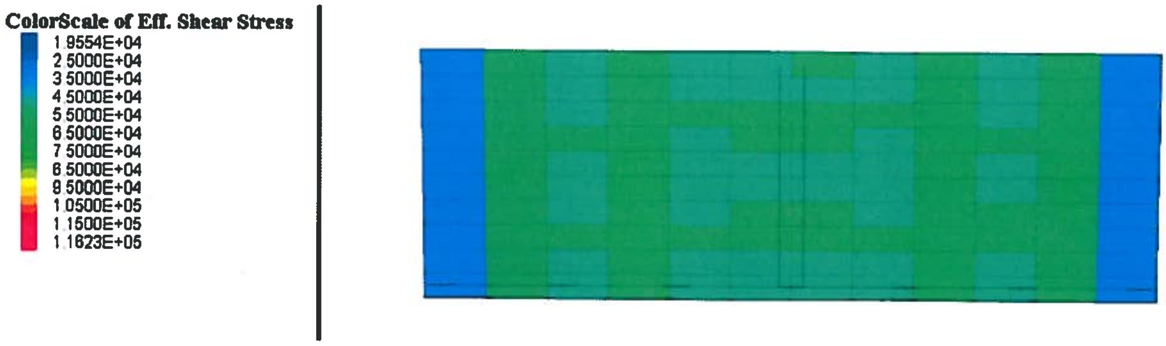

Figure 37 – Front View of the Shear Stress in the Polycarbonate Wall

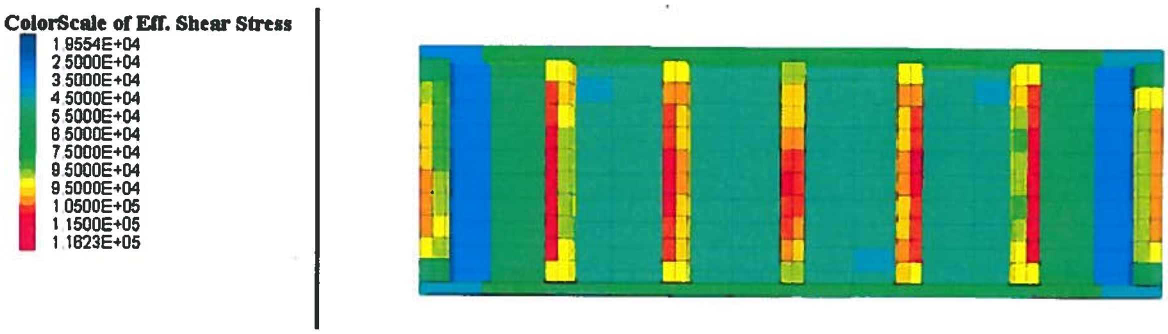

Figure 38 – Back View of the Shear Stress in the Polycarbonate Wall

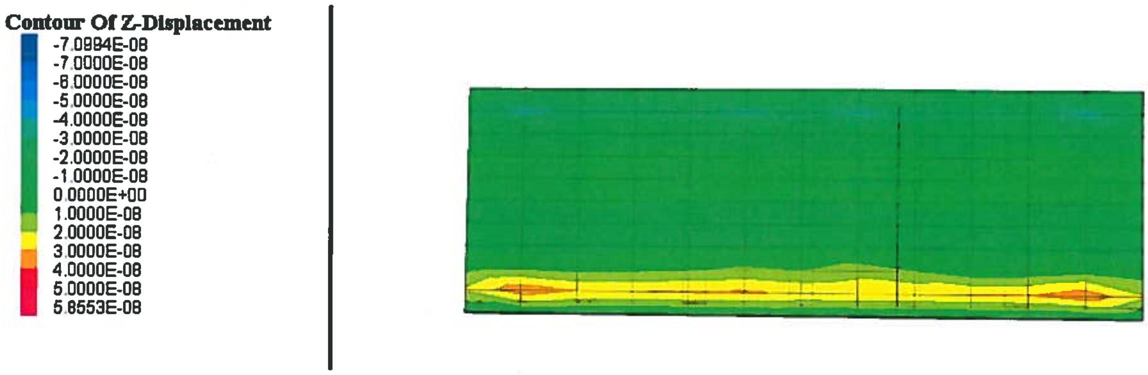

Figure 39 – Front View of the Contour of Z-Displacement of the Polycarbonate Wall

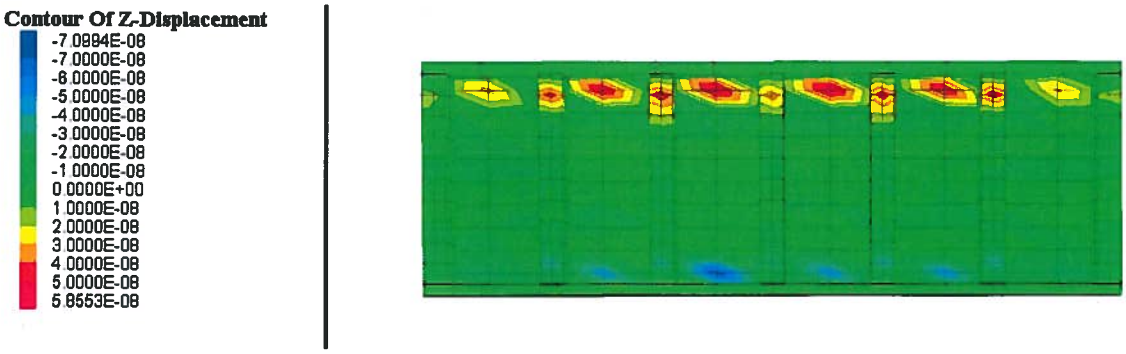

Figure 40 – Back View of the Contour of Z-Displacement of the Polycarbonate Wall

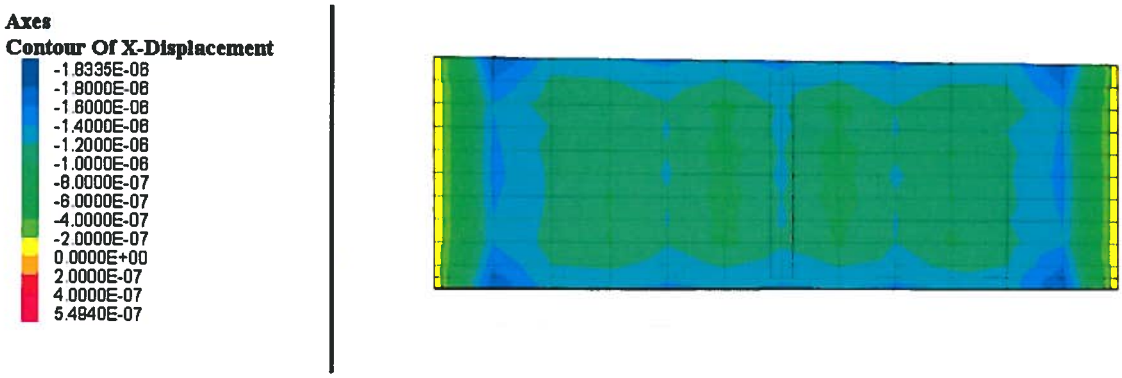

Figure 41 – Front View of the Contour of X-Displacement of the Polycarbonate Wall

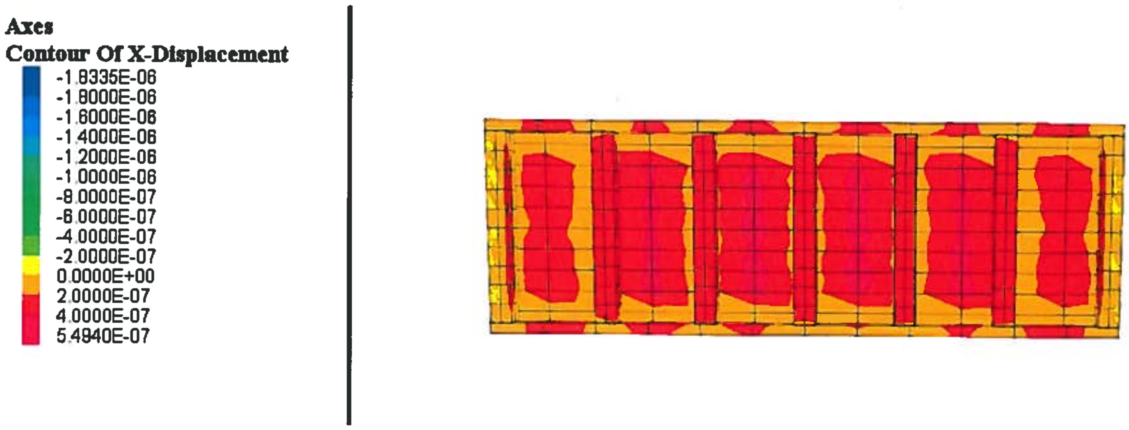

Figure 42 – Back View of the Contour of X-Displacement of the Polycarbonate Wall

The stresses and displacements of the stratums throughout the modeling process were also calculated and can be seen in Figures 43 – 46 below. Finally, Table 8 contains all of the maximum values for each calculated parameter during the modeling process.

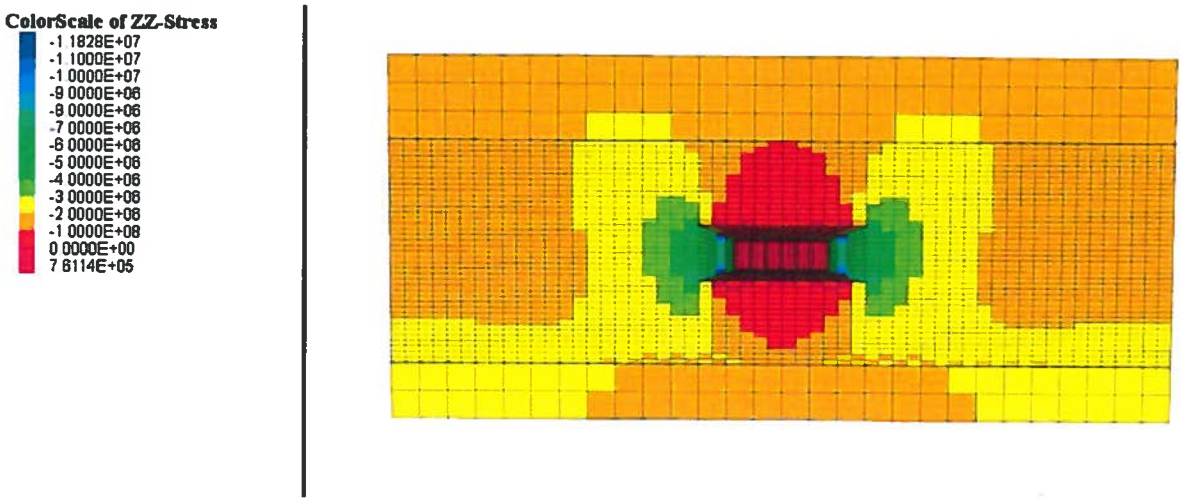

Figure 43 – Plot of the Contour of ZZ-Stress in the Ground

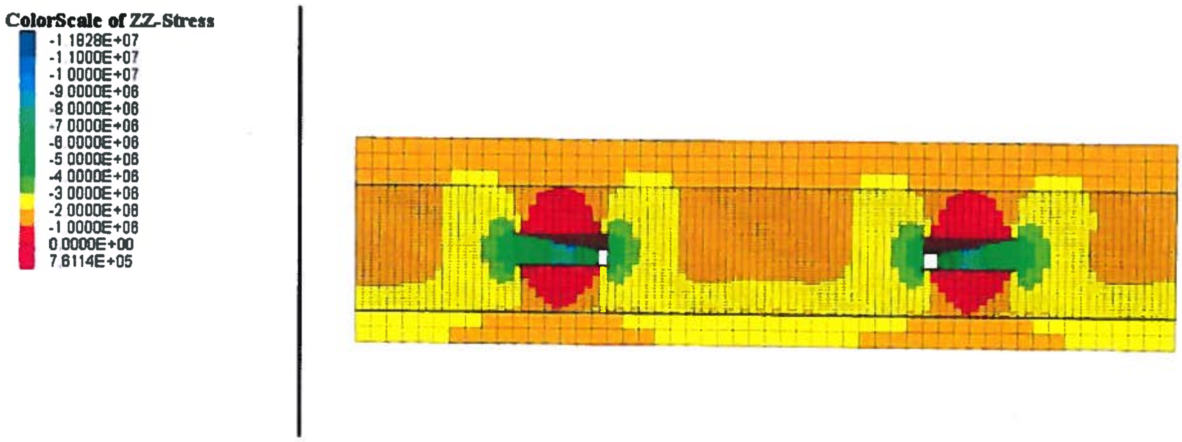

Figure 44 – Plot of the Contour of ZZ-Stress in the Ground

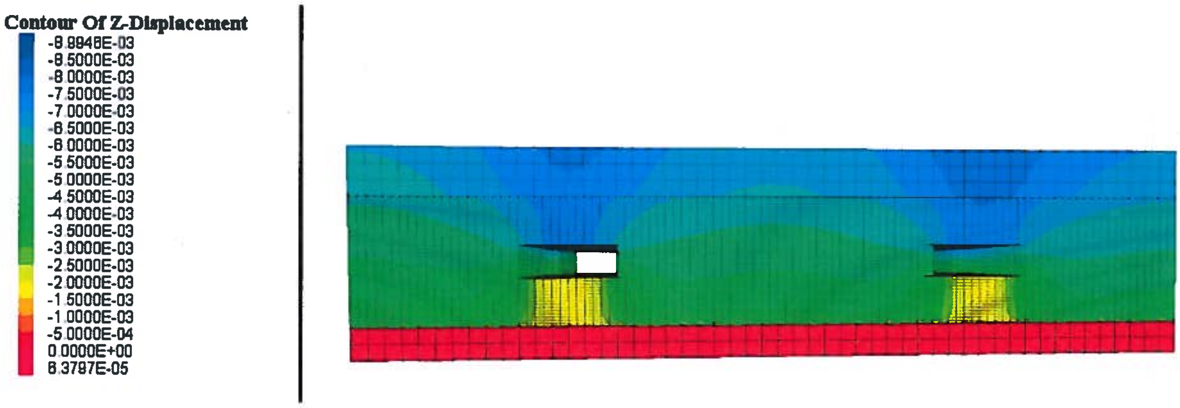

Figure 45 – Plot of the Contour of Z-Displacement of the Ground

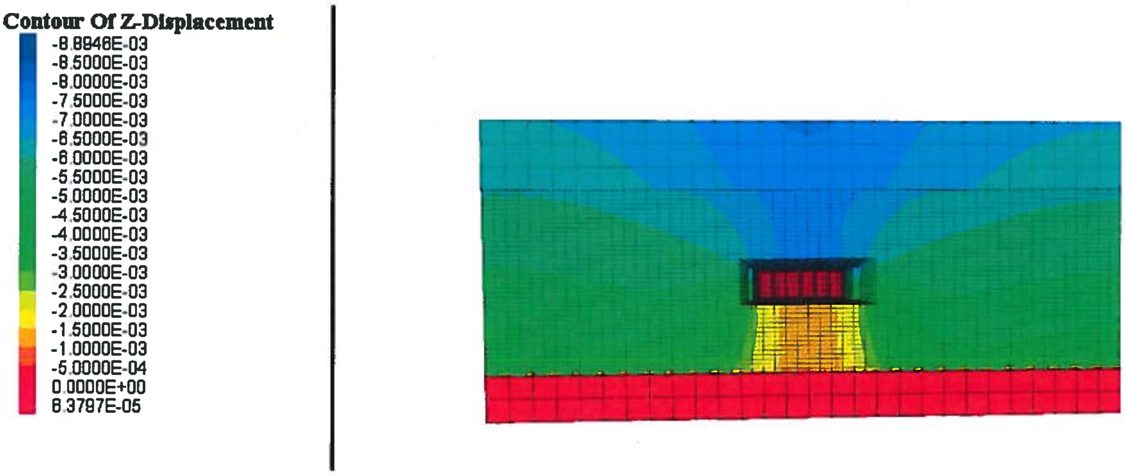

Figure 46 – Plot of the Contour of Z-Displacement of the Ground

Table 8 – FLAC3D Model Results

FLAC3D MODEL RESULTS		
	Max	
Bolts		
Stress	58702	Pa
Figure 6	8.51	psi
Polycarbonate Wall		
ZZ-Stress	140630	Pa
Figures 7 - 8	20.40	psi
XX-Stress	258880	Pa
Figures 9 - 10	37.55	psi
Shear Stress	116230	Pa
Figures 11 - 12	17	psi
Z-Displacement	-0.00000008	meter
Figures 13 - 14	-0.0000031	inch
X-Displacement	0.0000005	meter
Figures 15 - 16	0.000022	inch
Ground		
ZZ-Stress	-11828000	Pa
Figures 17 - 18	-1715.51	psi
Z-Displacement	-0.00899	meter
Figures 19 - 20	-0.3540	inch

The results from the FLAC3D modeling are very good with none of the maximum values being larger than allowed by material properties. The acceptable modeling results allowed the project to move forward with greater confidence and begin underground construction of the polycarbonate wall.

Additional Polycarbonate Wall Testing

Polycarbonate Wall Construction

After the initial testing of the polycarbonate wall system, it was determined that additional testing needed to be performed to test the system at the MSHA prescribed 15 PSI pressure. In order to achieve this pressure without detrimental effects to the shock tube, a smaller polycarbonate wall system was constructed in the smaller opening of the shock tube. The test setup used a similar design in a 91 inch by 91 inch opening. The smaller design included the full design height of six feet and used the whole 91 inch width. Also, one centered 66"x38" polycarbonate panel was used along with two smaller 66"x26.5" panels on either side. The vertical uprights and polycarbonate panels from the first round of shock tube testing were able to be used again for this test; however, new channel had to be ordered and drilled to accommodate the reduced upright spacing. Due to the overall height of these uprights being for a 72 inch height, a similar size reduction method from the previous testing was used to reduce the overall opening. Two steel channel pieces were bolted on either end of the top frame channel to contain oak boards used for the size adjustment. The two channel pieces were also bolted to the surrounding shock tube frame through pieces of angle that were welded into the web of the channel. Once all the steel framing and oak boards were in place, the polycarbonate wall system frame was fastened to the framing of the shock tube to simulate it being bolted to the floor and roof of a mine. One inch roof bolts, as shown in Figure 47, were installed on top to lock the oak boards and steel frame together; regular half inch bolts were used to secure the bottom channel of the wall system frame to the floor of the shock tube. Lastly, the polycarbonate panels were cut to size, drilled, and installed to finish the reduced system construction. The completed construction can be seen in Figure 48.

Figure 47 – Roof Bolts Installed

Figure 48 – Constructed Smaller Polycarbonate Wall System for Additional Testing

Polycarbonate Wall Testing

The additional testing also used pressure sensors to measure the explosive pressure experienced by the wall and a displacements laser to measure the displacement of the steel framing and polycarbonate panels. The testing setup for the additional testing was to embed two pressure sensors in the polycarbonate just outside each center vertical upright half way up each panel as shown in Figures 49 and 50. The laser was located in the same place for all tests and measured the deflection of the center polycarbonate panel. Each test was also captured with standard and high speed video to document and identify any movement or significant action that occurs during the blast test. The pressure for each test was created by hanging a C4 charge either 45 or 30 feet from the wall. This round of testing consisted of five tests.

Figure 49 – Sensor Placement for Additional Testing

Figure 50 – Sensor Embedded in Polycarbonate Panel

Testing Results

The smaller polycarbonate safe haven wall system also faired very well against the blast pressure applied during testing. The pressures and deflections were all recorded and can be seen in Table 9.

Table 9 – Additional Testing of Polycarbonate Wall System Results

Test Number	C4 Charge Weight (g)	C4 Charge Distance (ft)	Deflection (in)	Average Pressure (psi)	Average Impulse (psi-ms)	Laser Location
10191201	400	45	1.367989	13.49	65.11	Center of middle polycarbonate panel
10191202	500	45	1.522885	14.31	83.08	Center of middle polycarbonate panel
10191203	600	45	1.962377	15.43	101.21	Center of middle polycarbonate panel
10191204	650	45	2.278196	16.06	107.81	Center of middle polycarbonate panel
10191205	900	30	3.097167	25.56	150.07	Center of middle polycarbonate panel

As the results show, the wall was able to withstand up to 25.56 PSI without failing structurally. However, all of the bolts connecting the top channel of the wall frame and the channel holding the oak board size adjustment progressively sheared off during testing as seen in Figure 51. This is not a cause of concern since the roof bolts were still in place to connect all of the size adjustment and are what will be used to secure the wall to a mine roof. The shearing of the bolts may have also influenced the amount of deflection that occurred in the system. The results show that the amount of deflection increased with pressure and also as the number of bolts sheared off decreasing the rigidity of the system.

Furthermore, an approximately 20 and 12 inch crack developed following the final test in the center polycarbonate panel as seen in Figure 52. There was also a smaller three inch crack that was developed from previous testing as seen in Figure 53, however, this crack never increased in size throughout all the tests. The large crack was a direct result of testing; but the three inch crack is believed to have been induced by over tightening the bolts against the polycarbonate. This may have also been a factor in the development of the large cracks following the final test since the cracks originate from the bolts as Figure 52 shows. As a result, it is recommended that the bolts be hand tightened against the polycarbonate followed by a one second pulse from a 300 ft-lbs impact wrench to avoid over tightening.

Figure 51 – Sheared Bolts Connecting Channels

Figure 52 – Crack in Polycarbonate Following Final Test

Figure 53 – Crack from Previous Testing

The results from the additional testing allow the project to achieve the goal of developing a design that can withstand 15 PSI blast pressure. In all, the wall was tested nine times and demonstrated that it is a strong design capable of withstanding multiple blasts of over 15 PSI. Even though the impulse is still not where it needs to be, further research will have to be performed to develop a method in which to increase the duration of the blast.

Installation in Underground Coal Mine

The final task for the project was to install a full polycarbonate safe haven wall design in an underground coal mine. To achieve this goal, project members traveled to a chosen mine near Hazard, KY to take the measurements required to determine material specifications. The materials were then procured and prepared for the underground construction process. The steel framing was measured and cut using a plasma table for convenience. Due to the approximate 20 foot width of the chosen coal mine crosscut, the wall system was cut into two sections, 110 and 120 inches respectively, to aid in building the design in the confined conditions of an underground coal mine. The height of the wall was 82 inches, just under the height of the roof in the mine, to allow for any inconsistencies in the roof height and space to stand up the wall. The bolt system was the same as the previously tested design with addition of two bolts vertically since the wall was almost one foot taller. Finally, a door system was also developed and assembled in the frame before being transported to the mine as one piece.

The installation in an underground coal mine began by positioning the shorter preassembled door portion of the frame. This was done using clevises clipped into roof bolt plates already in the roof and chain hoists as seen in Figure 54 to lift the section up to a vertical position. Once the section was standing up, it was slid into position with the aid of a mining scoop machine. With the shorter channel section and door in position, 18 inch Hilti anchor bolts were inserted into the roof and floor through previous drilled holes in the top and bottom channel to secure the frame.

Figure 54 – Chain Hoist Clipped in a Clevis Hooked into a Roof Bolt

The installation of the door and shorter channel frame took one hour and 15 minutes. Using the preassembled door allowed the construction time of the wall to be reduced by an estimated three hours. The installed door section can be seen in Figure 55.

Figure 55 – Installed Preassembled Door and Shorter Channel Section

With the shorter channel frame sections installed, the next upright being placed in that section was able to be slid in the channel and bolted up as shown in Figure 56. Once the second upright was installed, the opening for the first polycarbonate panel was measured allowing the panel to be cut to size. After the panel was to size, it was placed against the steel frame uprights and marked for where the bolts holes needed to be drilled. While this was all taking place, the longer section of channel framing was being measured to fit the remaining opening. Bolt holes were also measured for the end upright against the rib and cut using an oxygen-acetylene torch. These processes took one hour to complete.

Figure 56 – Second Upright Installed

The next step in the installation process was to assemble the second longer section of channel frame and uprights. It was decided that the best way to install this section was to bolt the upright going against the opposite rib of the door to the top and bottom channel frame while on the ground. Then, the same method of clevises and chain hoists was used to lift the frame into place. Once the one upright and remaining channel frame was in place, the last three uprights were again slid into the channel and bolted to the channel. The channel frame had to be left at an angle in order to allow enough space between the already installed shorter channel section to slide in the uprights. With all the uprights bolted to the channel frame, the whole section was aligned with the first section using a sledge hammer and pry bar. It was then bolted to the floor and roof using the Hilti bolts as seen in Figure 57. Meanwhile, during this process the one polycarbonate panel that was measured was drilled and installed. These processes took one hour and 25 minutes and the results can be seen in Figure 58.

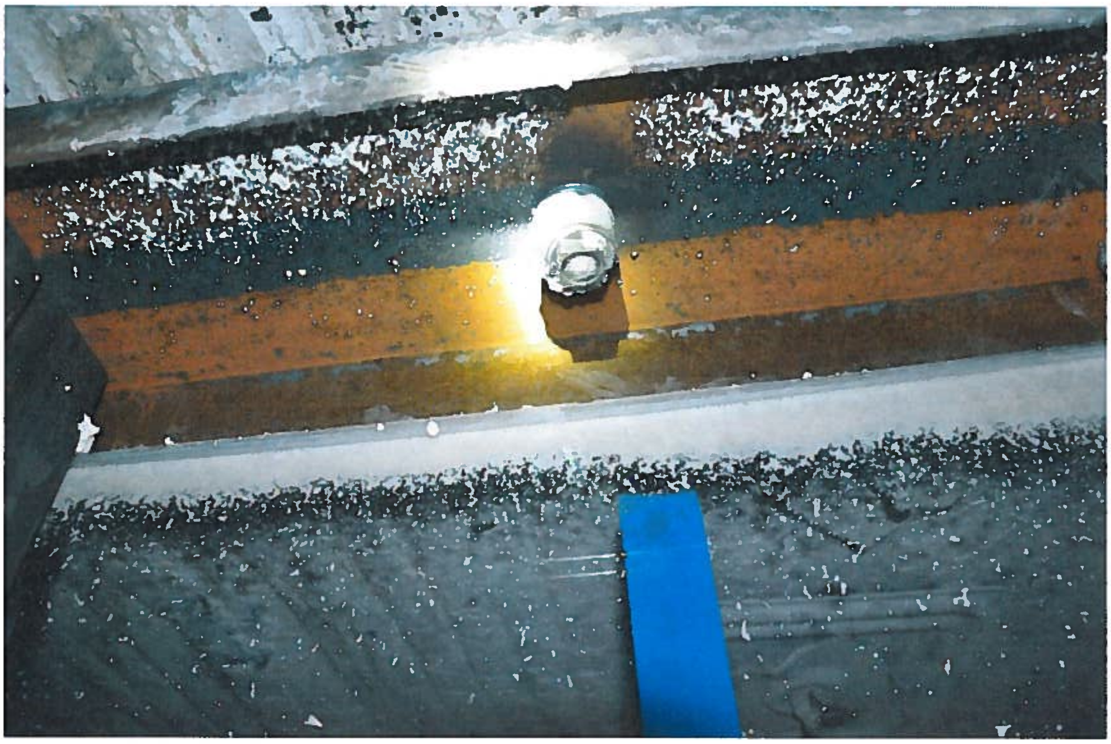

Figure 57 – Installed Hilti Bolt

Figure 58 – Completed Framing Installation

Following the installation of the steel frame, the remaining processes included measuring the polycarbonate panels to fit the openings between each vertical upright, marking bolt hole locations, drilling the holes, and installing the panels. This process was the most time consuming of the whole wall installation due to the limitations of tools and power. The polycarbonate panels were cut to size using a circular saw and drilled using forester bits while sitting on saw horses as seen in Figure 59. The installation of the remaining four panels took three hours and 15 minutes and the completed installation can be seen in Figure 60. All the bolts were tightened using a wrench and impact wrench and the before recommended tightening method to avoid cracking the polycarbonate.

Figure 59 – Cutting and Drilling Polycarbonate Panels

Figure 60 – All Polycarbonate Panels Installed

With the polycarbonate wall system installed, the final step was to seal the gaps with expanding Mine Foam. The areas seen in Figures 61 and 62 are where plywood was cut and placed to help fill gaps left between the wall and ribs due to irregular shapes of the ribs. The spaces left between the wall and the roof along with gaps between the steel frame and polycarbonate panels were all sealed with foam as seen in Figures 63 and 64. Sealing of the wall with the foam was done to verify the wall as a safe haven since it is required to maintain a stable, air-tight atmosphere. This process took 25 minutes.

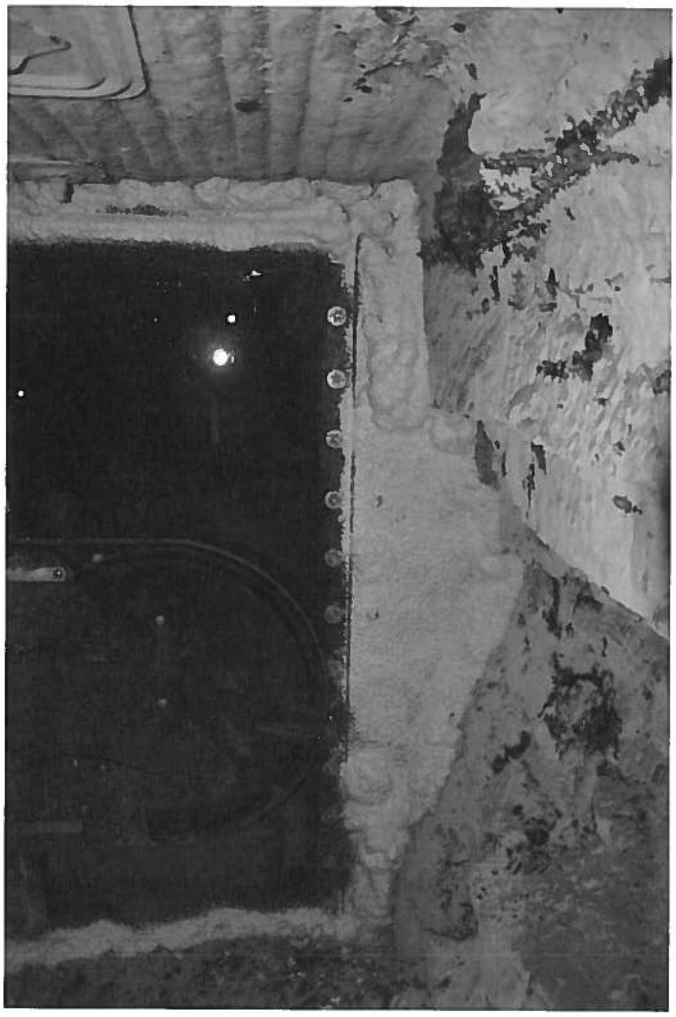

Figure 61 – Mine Foam Covered Plywood Used to Seal the Wall

Figure 62 – Plywood and Mine Foam Used to Help Seal the Wall

Figure 63 – Mine Foam Sealing the Space between the Frame and Floor

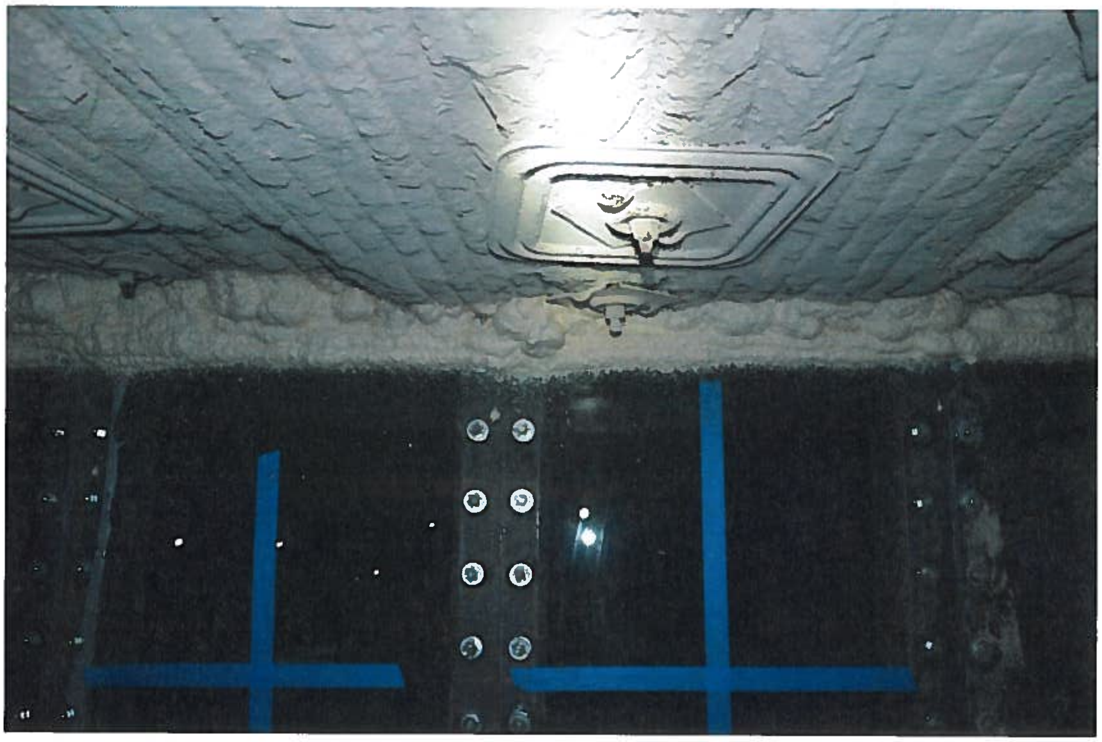

Figure 64 – Mine Foam Sealing the Space between the Frame and Polycarbonate and Roof

The polycarbonate safe haven wall installation and sealing was performed by eight people and took a total time of 7 hours and 20 minutes. A time limit goal of one shift was set prior to installation by the project team and that goal was met since no mining shift is normally less than eight hours. Therefore, the safe haven wall design installation is a comparable and justifiable alternative in its current design, meeting one goal of the project. The completed installation measured 228 inches wide and 82 inches tall. The door section provided a 32 inch opening, while the middle four sections were 30 inches, and the far left panel was 20 inches as seen in Figure 65. All of the polycarbonate panels were ¾" thick including the door panel. The final sealed installation is shown below in Figure 65 and 66.

Figure 65 – Final Sealed Installation Outside

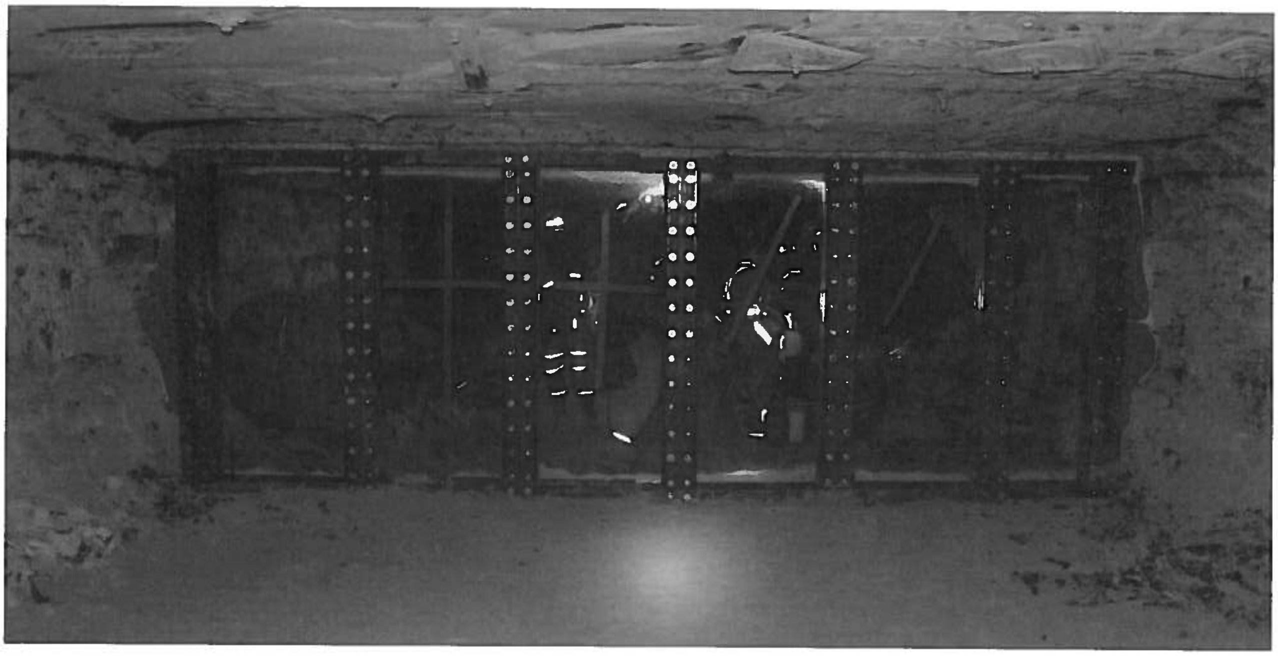

Figure 66 – Final Sealed Installation Inside

Installation Revision Suggestions

The installation of the polycarbonate safe haven wall system was a success. However, there are few issues that need revision following the first installation in an underground coal mine. First, a steel plate needs to be installed to help connect the two sections of steel channel framing. As Figures 67 and 68 show, the two channel sections of the frame did not align very well. This became apparent when trying to align the two sections during installation to create a square wall. Consequently, this created a difficult situation when trying to install the uprights.

A second recommended revision would be to develop a better method of sealing between the wall and the coal pillars on each side. Expanding Mine Foam was used for the prototype installation but would not provide enough resistance over that span in case of an actual explosion. In future installations, bags which can be filled with a cementious grout will be placed between the wall sides and coal pillar and then filled. The expanding bags will fill the void and provide sufficient resistance in the event of an explosion. These bags have been used in coal mines in the past for 20 PSI mine seals and have been proven to be an effective solution to this type of scenario.

A third revision would be to the door system. For the first iteration, the door performed very well, however, it did not seal very well because of the flex in the polycarbonate. A steel frame surrounding the circular polycarbonate window would help add rigidity to the door and allow it seal better. There are also alternative latching mechanisms that could be used to ensure a higher quality seal.

There is a possibility that the wall could be constructed outside the mine in two pieces. In this situation, the two panels would be taken into the mine completely fitted with polycarbonate and uprights. The only tasks remaining underground would be standing up the sections and attaching them to the roof and floor and aligning them to each other with a steel plate for square installation. The wall could then be sealed with grout bags and mine foam. This would allow for further reduction in installation times.

Finally, proper drilling equipment is needed to properly install the Hilti anchor bolts. During installation, the drill being used had problems drilling through the floor and roof causing the bolts to require washers to make up the distance to allow the bolts to anchor properly as shown in Figure 69. For this being the first installation, the process went very well but these revisions would aid in the design and installation process for future iterations.

Figure 67 – Intersection of the Top Two Channel Sections

Figure 68 – Intersection of the Bottom Two Channel Sections

Figure 69 – Polycarbonate Washers used on Hilti Bolts

Polycarbonate Safe Haven Wall Door System

Door System Design

Passage through the polycarbonate safe haven wall is possible through a man door installed in one of the panels of the wall. The door is constructed of polycarbonate material as well. The door was designed to withstand the 15 PSI curve prescribed by MSHA. This design was later tested in the University of Kentucky Explosives Research Team (UKERT) shock tube. The man door was designed to have a 30 inch opening to allow passage by miners into the safe haven.

For the door design, HAZL was used for initial designs and prototyping. The code is limited distribution through the Army Corps of Engineers Protective Design Center. "HAZL performs a single degree of freedom (SDOF) analysis to calculate the glazing response to a blast loading and a debris transport model for predicting fragment trajectory. The program allows modeling of monolithic glass or plastic windows, laminated windows, insulated glass units and windows retrofitted with anti-shatter film. The user inputs the window geometry, glazing type, material and thickness, and blast load. The blast load can be input manually, read from an input file, or generated for a given charge weight and standoff distance. Output includes the hazard level, glazing response parameters, reaction loads, and required frame bite. Results can be displayed either in a text format or as graphical plots. The program can also produce pressure-impulse (P-i) curves for the specified window to be used in vulnerability and security planning analyses. " (HAZL, 2013)

Based on previous experience testing fenestration systems with polycarbonate material, two thicknesses (0.75 inch and 1 inch) were calculated using HAZL to determine the thickness necessary for the door material. Each thickness was calculated using a door size of 30 inches by 30 inches. This design assumption should hold true even though the door assembly is rounded. The maximum span of the circular opening is 30 inches. The first thickness evaluated was 0.75 inches. For initial consideration a PI curve was generated for the 0.75 inch thick material. Figure 70 shows the PI curve for the 0.75 inch door. The lower asymptote of the curve approaches 15 PSI.

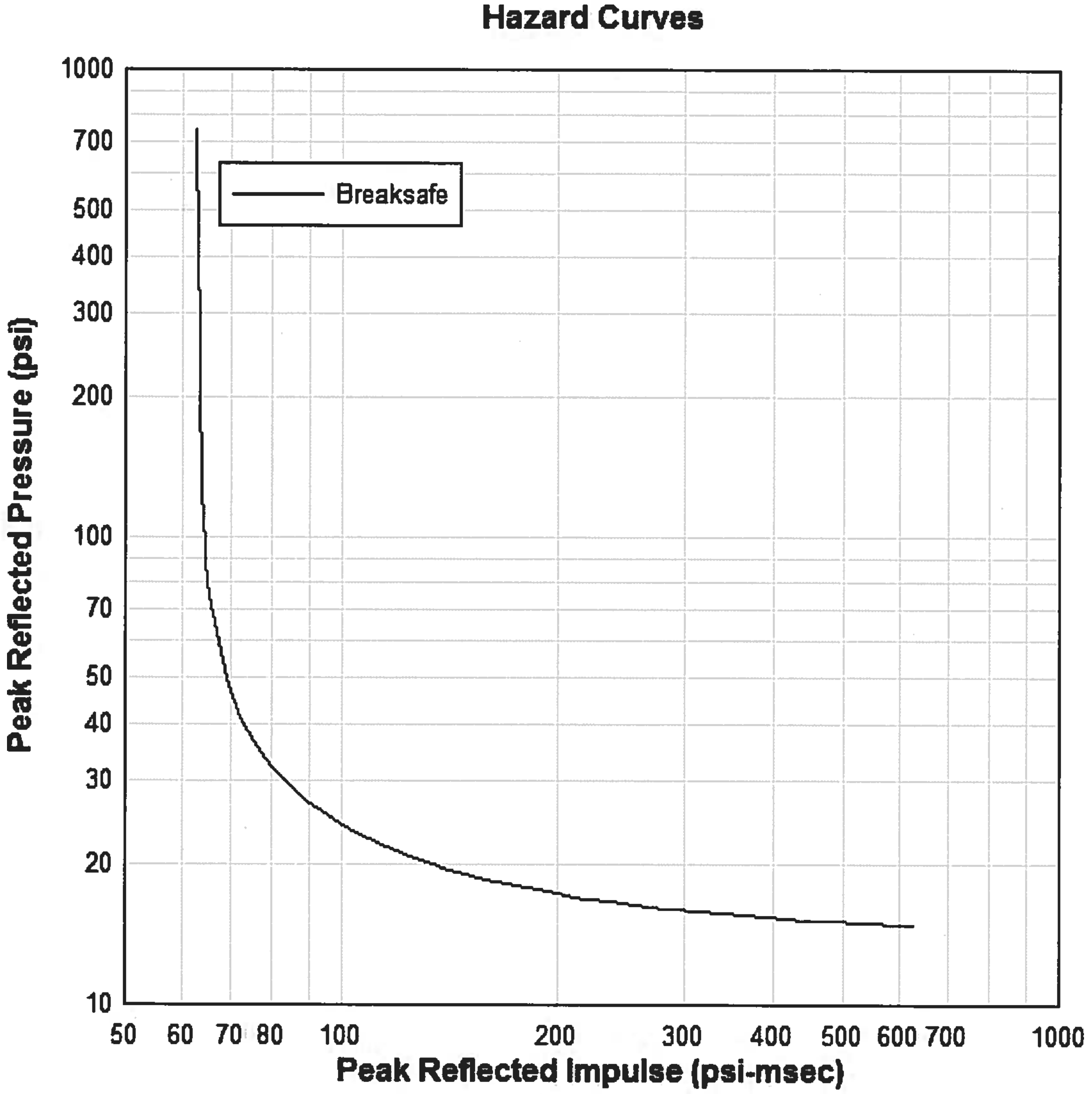

Figure 70. PI Curve for 0.75 Inch Thick Polycarbonate Door

Further analysis using the functions of HAZL was necessary to determine the performance of the door under the loading described by the MSHA 15 PSI curve. A CSV file was generated for use in the HAZL code for analysis. Output from the model predicted that the "glass does not crack and is retained in frame." The required bite for this condition is 0.887 inches which is satisfied by the door overlap which is approximately 2 inches. The design also resulted in a maximum effective static capacity of 39.96 PSI. Based on the results of the HAZL analysis, 0.75 inches is sufficient for material thickness of the door system. Complete output from the HAZL program can be found in Appendix A.

HAZL was also used to calculate the performance of 1 inch polycarbonate material for the door system. Figure 71 shows the PI curve for 1 inch polycarbonate material subjected to the MSHA design curve. For the 1 inch thickness the asymptote approaches 25 PSI.

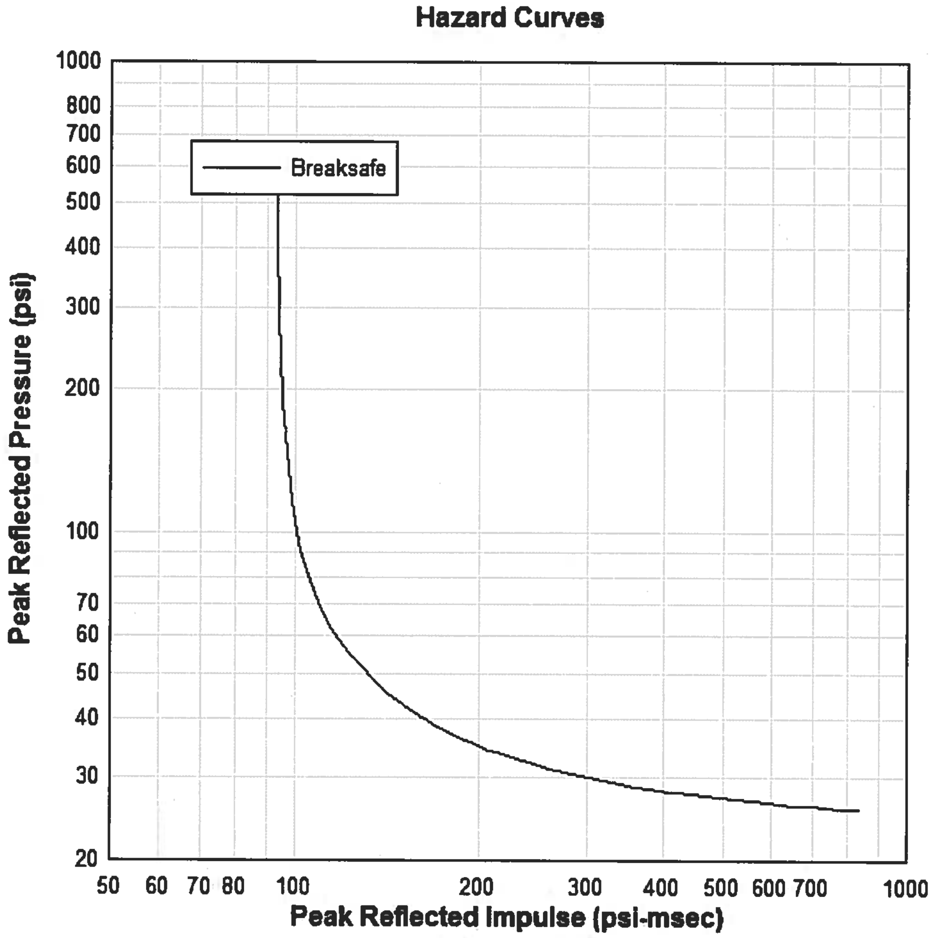

Figure 71 – PI Curve for 1 Inch Thick Polycarbonate Door

Utilizing the same MSHA CSV file, further analysis was performed using HAZL for the 1 inch material. The output predicted the same performance where the "glass does not crack and is retained in the frame." The maximum effective static capacity according to HAZL for the 1 inch polycarbonate is 64.84 PSI with a recommended minimum bite of 0.852 inches. Complete HAZL output for the 1 inch material can be found in Appendix B.

HAZL calculations show that either material is acceptable for use in the door system. At first glance, the 1 inch material provides a better safety factor than the 0.75 inch material. Previous testing experience has shown that HAZL will underestimate the resistance of polycarbonate material; thus 0.75 inch material was selected for testing.

One additional HAZL calculation was performed incorporating the 0.75 inch material and the actual tested wave form from the UKERT shock tube. Another CSV file was produced based on actual data taken from the test. The model predicted a no break condition where the glass does not crack. The model also predicted a maximum deflection of 2.08 inches. This corresponds well to the measured deflection of the panels reported in Table 9. Confirmation of the model provides confidence in the design thickness of 0.75 inches. Complete output from the HAZL model for the 0.75 inch thick door subjected to the test load can be found in Appendix C.

Latch and hinge components were tested rather than evaluated through calculations due to the complexity of the system and difficulty of accurately modeling their response. Through the combination of design calculations and testing, the polycarbonate door system was validated for performance as a 15 PSI safe have door.

Door System Construction

The polycarbonate safe haven wall door system testing was performed after its installation in the underground coal mine due to its availability. The door system was installed in the smaller framing system used for the earlier discussed additional testing section. Due to the door system being designed for a 32 inch opening for the underground mine installation, one of the center uprights had to be widened two inches to accommodate it. Once the upright was positioned, the polycarbonate door panel was fit to the newly positioned upright's bolt holes. With the holes in the polycarbonate matching those of the steel uprights, the one inch thick circular polycarbonate door and hinges were attached to the rest of the polycarbonate panel and steel. The hinges for the door bolted through the polycarbonate and steel frame just as the bolts holding the polycarbonate panels to the uprights. The latch mechanism was also similarly installed at this point through one bolt hole as seen in Figures 72 and 73. Finally, since one upright was widened, the old polycarbonate panel connected to the widened upright had to be reduced and new holes drilled to fit new system. The installed door system for testing can be seen in Figure 74 – 77.

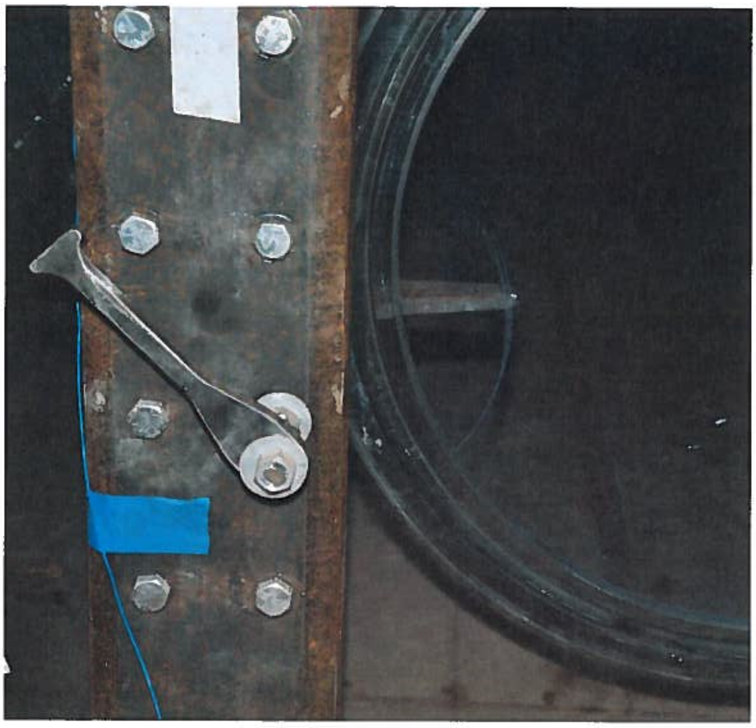

Figure 72 – Inside View of Latch Mechanism

Figure 73 – Outside View of Latch Mechanism

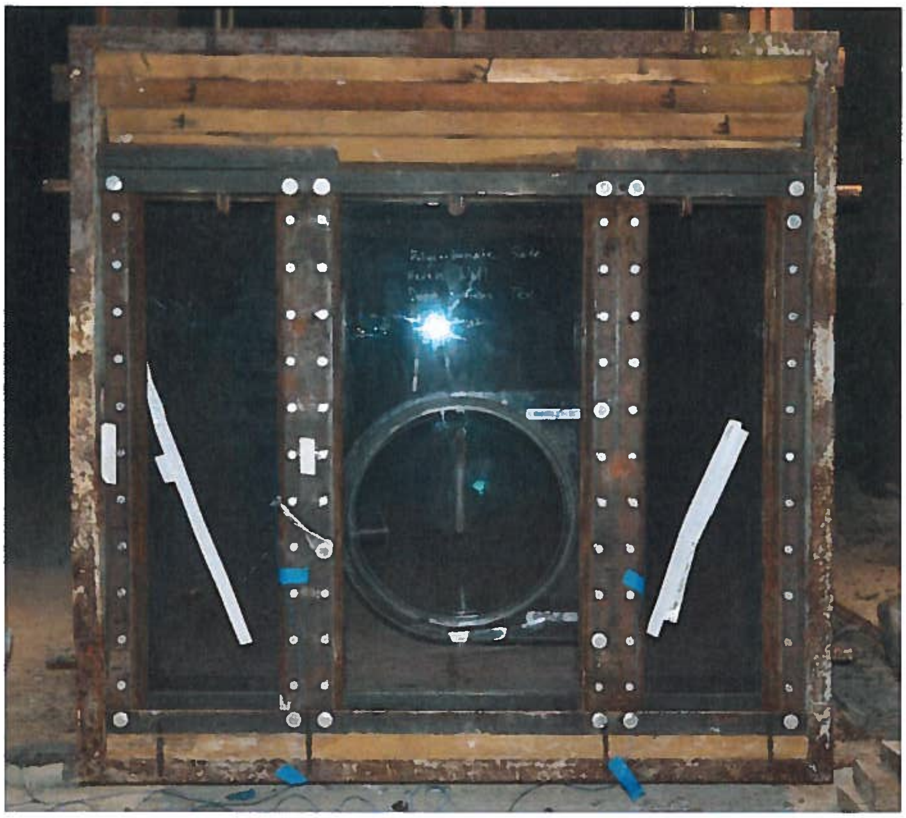

Figure 74 – Installed Door System for Testing (Inside)

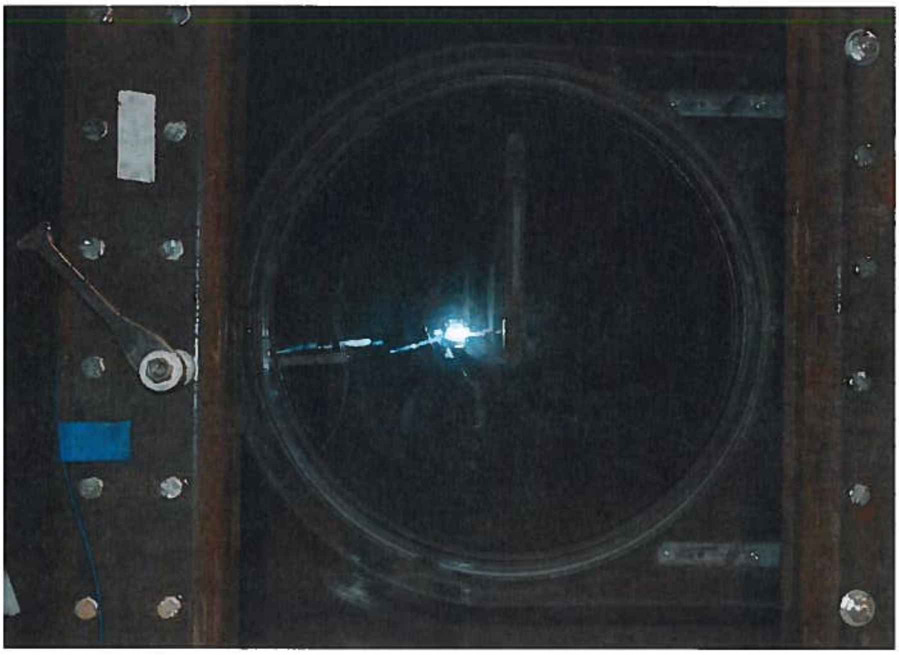

Figure 75 – Installed Door (Inside)

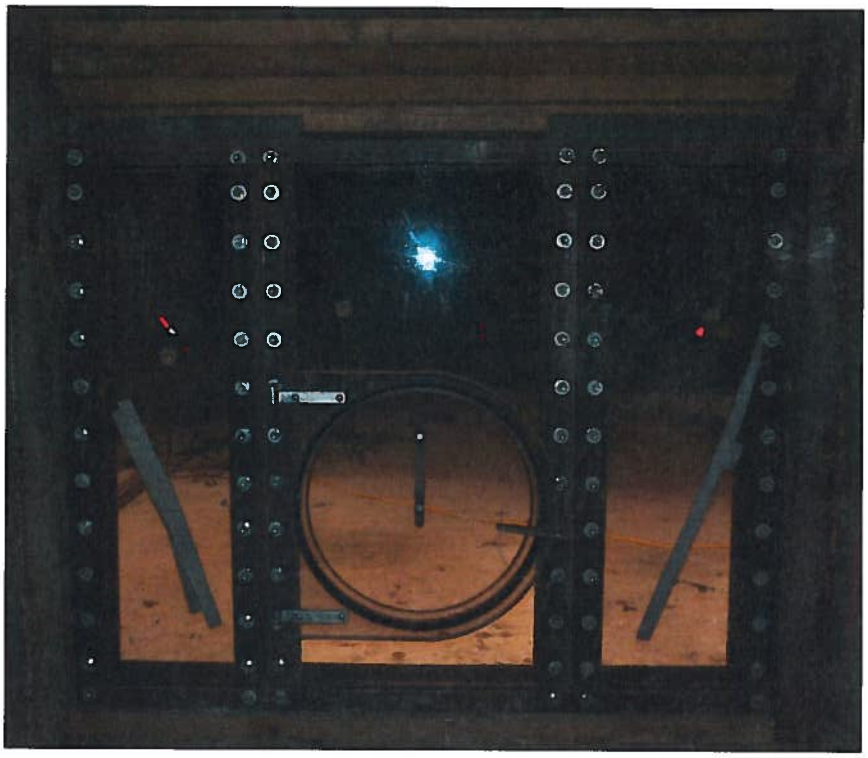

Figure 76 – Installed Door System for Testing (Outside)

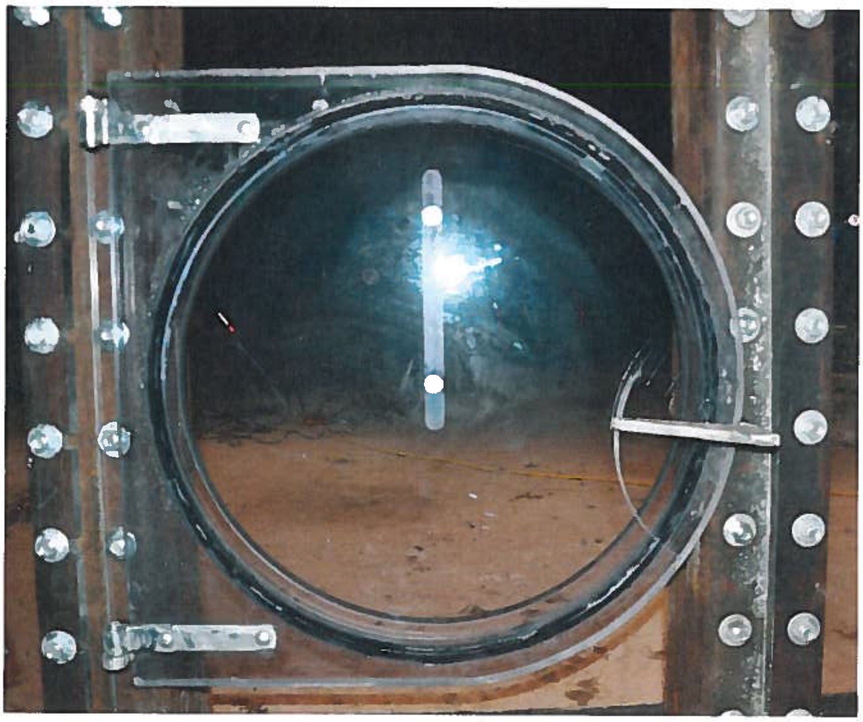

Figure 77 – Installed Door (Outside)

Door System Testing

The polycarbonate safe haven door system testing again used pressure sensors to measure the explosive pressure being experienced by the door and wall. The testing setup for the door system testing used two pressure sensors in the polycarbonate just outside each center vertical support just as the additional wall testing. The first sensor was placed half way up the left panel and the second was placed 24 inches up from the bottom of the right panel as seen in Figure 78. Each test was also captured with standard and high speed video to document and identify any movement or significant action that occurs during the blast test. The pressure for each test was created by hanging a C4 charge 45 feet from the door system. This round of testing consisted of three tests.

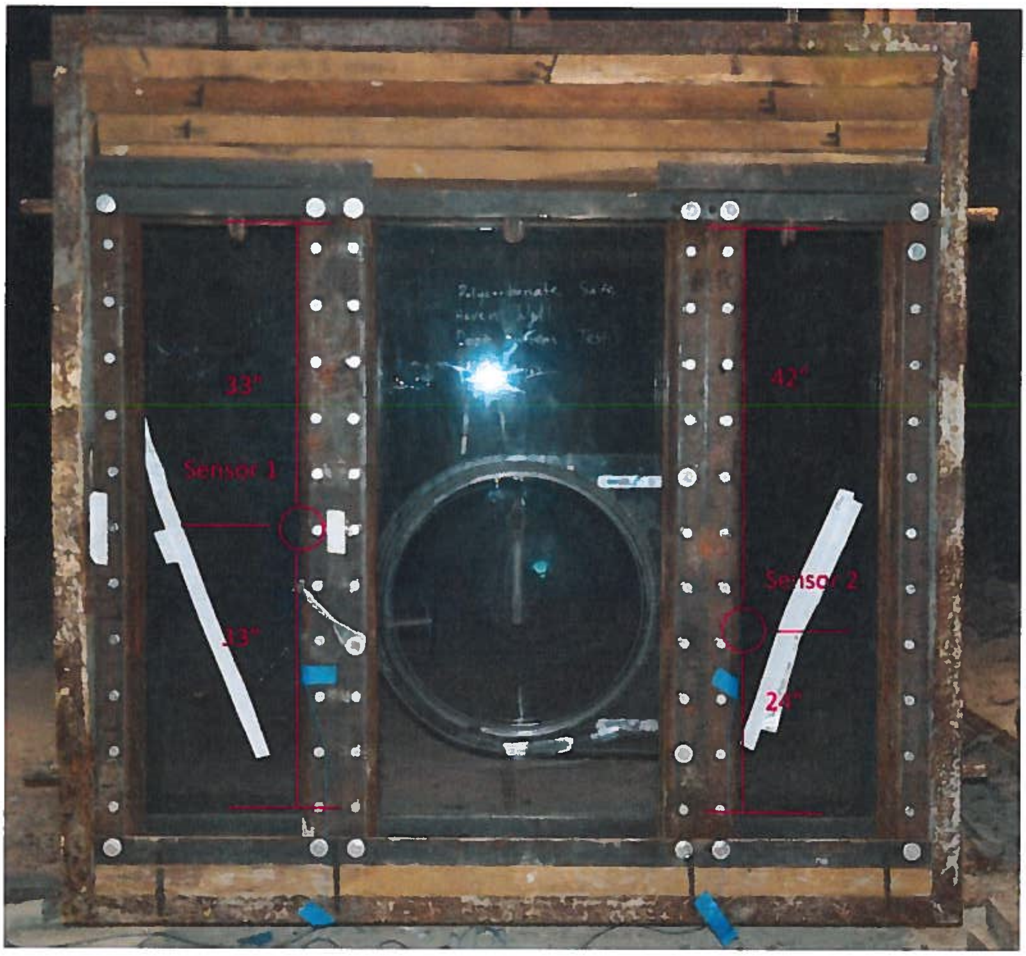

Figure 78 – Sensor Arrangement for Door Testing

Door System Results

The door system performed exceptionally well during the blast testing. The design held up to all three tests and no damage occurred to any portion of the system. The latch mechanism and hinges were also still tight and structurally sound after each test. The pressures and impulses from the blast testing were recorded and can be seen in Table 10.

Table 10 – Door System Results

Test Number	C4 Charge Weight (g)	C4 Charge Distance (ft)	Average Pressure (psi)	Average Impulse (psi-ms)
12201201	650	45	15.26	101.13
12201203	650	45	15.34	108.11
12201204	750	45	16.58	127.61

As the Table show, the door system was also subjected to 15 PSI blast pressures multiple times and showed no damage. Again, the impulse is to below the MSHA specification; however, the results from the door system proves that the door system design is strong and provides a quality option for travel through the polycarbonate safe haven wall system.

Overall Cost Advantage

One of the main objectives of this research was to develop an alternative to refuge options currently available to underground coal mines. The typical method mines use are refuge chambers which can cost well upwards of $80,000 depending on personnel capacity. With the use of safe haven walls, walls can be constructed on both ends of a crosscut with life saving/sustaining supplies stored between the walls. Another option which would only require one wall consists of a room created by the continuous miner into a solid coal block. Three walls of the room would be coal while the opening could be closed with a wall.

The designed polycarbonate safe haven wall consists of four main components which greatly influence the overall cost: polycarbonate, steel, door fabrication, and bolts. While not every polycarbonate wall will be identical due to changing cutting heights and widths, a summary of the costs for the wall installed in the mine are given in Table 11. The steel support line includes the C-Channel and the vertical hollow tube sections. The bolts line item includes the bolt, washers, and nut.

Table 11. Material Cost for Polycarbonate Safe Haven Wall

Item	Unit Price	Quantity	Price
Polycarbonate Panel	$1,161.37	6	$6,968.22
Steel Support	$3,931.00	1	$3,931.00
Door Fabrication & Drilling	$2,853.00	1	$2,853.00
Grade 50 0.75 inch Bolts	$5.83	180	$1,049.40
	Material Cost		**$14,801.62**

The constructed wall was approximately 7 feet tall and 20 feet wide which would be sufficient cover a large portion of the underground coal mines in Kentucky. In addition, mines can plan in advance where to station these walls so that cutting height and width can be slightly reduced to decrease the overall costs of the wall. The price shown in Table 11 does not include everything that would be required to install the wall. Several point-anchor bolts, as described in a previous section, will be required. Material to seal the air gaps will also be required.

The total material cost of $14,800 was for this prototype design. With the addition of materials not listed in the table, a total material cost of approximately $16,000 is realistic and reasonable. For a total installed cost, mining personnel and equipment usage must be accounted for. After construction and installation of the prototype, it is believed that several time-consuming steps could be done prior to taking the materials underground (e.g. polycarbonate drilling and some steel structure assembly). However, the prices shown in Table 12 include the costs of three miners for an eight hour shift as well as a piece of equipment (a mine scoop) used for two hours.

Table 12. Total Installed Cost of Polycarbonate Wall

Item	Unit	Quantity	Hours	Price
Material	$16,000	1	N/A	$16,000
Mining Personnel	$75	3	8	$1,800
Equipment Usage (Scoop)	$250	1	2	$500
		Installed Cost		**$18,300**

A $18,300 price tag for an installed safe haven wall will be a very attractive for mine operators in Kentucky and throughout the region. Even when two walls are required, the total installed cost will be less than half of currently implemented refuge chambers. Adding the cost of supplies necessary to complete the safe haven, the final product would be competitive from a cost standpoint. Another cost saving measure will be the volume of materials ordered. As with most goods, volume pricing will further decrease the overall costs to these mines.

When compared to concrete block walls, the material costs of the polycarbonate panel are higher than that of block and mortar. However, there are several advantages polycarbonate has over the block walls. First, the construction time of double, or triple wythe concrete blocks can take anywhere from 1-3 shifts depending on mining location. Second, the material handling of the heavy concrete blocks can lead to injuries to mining personnel. While the steel of the polycarbonate wall is also heavy, equipment can aid in movement and placement versus each individual concrete block requiring a miner to carry and place them. Third, all materials required for the entire polycarbonate wall were transported from the surface to the location using a single scoop with trailer and then unloaded by hand. Finally, the polycarbonate wall is clear while the concrete blocks are not. In the event of an explosion, mine rescue teams can simply look through the wall to see if any miners are taking refuge inside. For concrete block walls, a large, heavy door must be opened. This task eats up time and may not allow teams to reach miners in distress.

One final cost saving measure is that the polycarbonate panels are detachable and movable. As the panels consist of approximately half of the material cost, this can be a great advantage. With standardized sizes within a mine, the polycarbonate panels can be unbolted from the steel frame and moved wherever they are needed. For example, in mines where sections are sealed off and never to be revisited, the panels can be unbolted and re-installed on new steel frames elsewhere in the mine. While this concept may not be beneficial in an active mining section, removing them from soon to be sealed off areas is a great way for the mines to save money. This option is not possible with concrete block walls. Therefore, in larger mines where multiple wall are constructed, the total cost of the polycarbonate safe haven wall may be lower for the overall life of the mine.

Conclusion

The project was able to produce a successful wall design through both modeling and testing and then proved feasible with the construction within an active coal mine. The design met all project goals of being lightweight for easy installation, transparent to allow trapped miners to easily rescued, able to be installed in one shift, and provide cost advantages over currently used refuge alternatives. The polycarbonate safe haven wall system was also able to withstand 15 PSI blast pressure multiple times. The successful design was made out of HSS 8"x4"x0.5" vertical supports and held in place by C10x10 channel with one inch polycarbonate panels bolted to the uprights. The dimensions of the design were able to reach an installed width of 228 inches and a height of 82 inches. A door system for the polycarbonate safe haven wall was also successfully developed to allow easy passage through the wall system and installed as part of the wall system in an underground coal mine. The door system was also able to withstand 15 PSI blast pressures multiple times. With the project complete and all goals achieved, there is still room for improvement in the design along with the installation processes to help develop new safe haven alternatives for use in underground coal mines.

References

Department of Labor (2008), "Mine Safety and Health Administration 30 CFR Parts 7 and 75 Refuge Alternatives for Underground Coal Mines: Final Rule", http://www.msha.gov/REGS/FEDREG/FINAL/2008finl/E8-30669.pdf, September 2011.

HAZL, United States Army Corps of Engineers Protective Design Center Website: https://pdc.usace.army.mil/software/hazl/ 2013.

Appendix A

HazL output for 0.75 Inch MSHA Curve.
HazL v1.2 Analysis Details
HazL - Tue, Jan 15, 2013, 19:24
================
INPUT PARAMETERS
================
Analysis Mode : Threat Analysis
System Of Measure: English
Hazard Level Based on: Flight
Threat Input:

Load read from file = C:\Users\Braden\Documents\HAZL\Useful Output\MSHA 15 PSI Curve.csv
Window Input:

Stiffness = Moore Resistance Function
Glazing Type = Polycarbonate
Prob of fail (#/1000) = 500.00
Height = 30.00 in
Width = 30.00 in
Actual Thickness = 0.750 in
Ht. of sill above floor = 2.00 in
===============
RESULTS SUMMARY
===============
Window Parameters

Xu	= 2.964 in	Maximum Static Deflection
Ru	= 39.96 psi	Maximum Effective Static Capacity
Bite	= 0.887 in	Required Bite
Stress	= 9500.00 psi	Peak Glass Stress

Window Response

Glass does not crack and is retained in frame.
==============================
Hazard level = No Break
==============================
Peak glass stress = 4921.160769 psi
Maximum acceleration = 268.96 g's at 91.97 ms
Maximum velocity = 221.70 in/s at 95.21 ms
Maximum displacement = 2.14 in at 97.76 ms
Minimum acceleration = -2059.39 g's at 0.17 ms
Minimum velocity = -203.14 in/s at 100.49 ms
Minimum displacement = -0.53 in at 206.43 ms

Static Edge Shears - Glazing Only:

VX = 593.40*SIN(0.10*X) + 39.96*W lbs/in
VY = 593.40*SIN(0.10*Y) + 39.96*W lbs/in
R = -2337.65 lbs

- X in the above equation varies from zero up to the long dimension of the window in inch.
- Y in the above equation varies from zero up to the short dimension of the window in inch.
- W in the above equations is the width of the window frame that is exposed to blastin inch.
- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 6311.18 lbs or 210.37 lbs/in
VY = 6311.18 lbs or 210.37 lbs/in

Appendix B

HazL output for 1 Inch MSHA Curve.
HazL v1.2 Analysis Details
HazL - Tue, Jan 15, 2013, 19:29
================
INPUT PARAMETERS
================
Analysis Mode : Threat Analysis
System Of Measure: English
Hazard Level Based on: Flight
Threat Input:

Load read from file = C:\Users\Braden\Documents\HAZL\Useful Output\MSHA 15 PSI Curve.csv
Window Input:

Stiffness = Moore Resistance Function
Glazing Type = Polycarbonate
Prob of fail (#/1000) = 500.00
Height = 30.00 in
Width = 30.00 in
Actual Thickness = 1.000 in
Ht. of sill above floor = 2.00 in
================
RESULTS SUMMARY
================
Window Parameters

Xu = 2.824 in Maximum Static Deflection
Ru = 64.84 psi Maximum Effective Static Capacity
Bite = 0.852 in Required Bite
Stress = 9500.00 psi Peak Glass Stress
Window Response

Glass does not crack and is retained in frame.

==============================
Hazard level = No Break
==============================
Peak glass stress = 3521.587137 psi
Maximum acceleration = 193.57 g's at 89.74 ms
Maximum velocity = 170.85 in/s at 93.12 ms
Maximum displacement = 1.45 in at 95.88 ms
Minimum acceleration = -2313.91 g's at 0.15 ms

Minimum velocity = -154.90 in/s at 110.48 ms
Minimum displacement = -0.33 in at 3.84 ms
Static Edge Shears - Glazing Only:

VX = 962.82*SIN(0.10*X) + 64.84*W lbs/in
VY = 962.82*SIN(0.10*Y) + 64.84*W lbs/in
R = -3792.94 lbs
- X in the above equation varies from zero up to the long dimension of the window in inch.
- Y in the above equation varies from zero up to the short dimension of the window in inch.
- W in the above equations is the width of the window frame that is exposed to blastin inch.
- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 9451.48 lbs or 315.05 lbs/in
VY = 9451.48 lbs or 315.05 lbs/in

Appendix C

HazL output for 0.75 Inch Test Data Curve
HazL v1.2 Analysis Details
HazL - Tue, Jan 15, 2013, 19:48
===============
INPUT PARAMETERS
===============
Analysis Mode : Threat Analysis
System Of Measure: English
Hazard Level Based on: Flight
Threat Input:

Load read from file = C:\Users\Braden\Documents\HAZL\Useful Output\Door Test Data curve.csv
Window Input:

Stiffness = Moore Resistance Function
Glazing Type = Polycarbonate
Prob of fail (#/1000) = 500.00
Height = 30.00 in
Width = 30.00 in
Actual Thickness = 0.750 in
Ht. of sill above floor = 2.00 in
===============
RESULTS SUMMARY
===============
Window Parameters

Xu = 2.964 in Maximum Static Deflection
Ru = 39.96 psi Maximum Effective Static Capacity
Bite = 0.887 in Required Bite
Stress = 9500.00 psi Peak Glass Stress
Window Response

Glass does not crack and is retained in frame.
============================
Hazard level = No Break
============================
Peak glass stress = 4748.676789 psi
Maximum acceleration = 774.67 g's at 0.17 ms
Maximum velocity = 534.80 in/s at 3.24 ms
Maximum displacement = 2.08 in at 5.96 ms
Minimum acceleration = -935.96 g's at 6.13 ms
Minimum velocity = -599.54 in/s at 8.52 ms

Minimum displacement = -1.54 in at 66.25 ms

Static Edge Shears - Glazing Only:

VX = 593.40*SIN(0.10*X) + 39.96*W lbs/in

VY = 593.40*SIN(0.10*Y) + 39.96*W lbs/in

R = -2337.65 lbs

- X in the above equation varies from zero up to the long dimension of the window in inch.
- Y in the above equation varies from zero up to the short dimension of the window in inch.
- W in the above equations is the width of the window frame that is exposed to blastin inch.
- R in the above equations is the uplift corner force in pounds.

Dynamic Edge Shears - Glazing Only:

VX = 3356.54 lbs or 111.88 lbs/in

VY = 3356.54 lbs or 111.88 lbs/in

Appendix D

CRSI

Concrete Reinforcing Steel Institute
933 North Plum Grove Road
Schaumburg, Illinois 60173
p: 847.517.1200 | f: 847.517.1206
www.crsi.org

Project		Sheet No of
Made By	Checked By	Date
Subject		Project No.

Bolt Design

3/4" Grade 5 bolts

Strengths - Machinery's Handbook 28th Edition
Proof = 85ksi
Tensile = 120ksi
Yield = 92ksi
Shear ≈ 60% Tensile = 72 ksi

Load: 30psi with Dynamic Load Factor = 2
∴ 60psi

Panel Area 66" x 38"
$A = 2508 in^2$

Bolt Area (A_b)
$A_b = \frac{\pi d^2}{4} = \frac{\pi (0.75)^2}{4}$
$A_b = 0.442 in^2$

Shear Design

5000psi of shear on panel from ANSYS model (1 edge)
5000psi x 1in thick = 5000lb/in
shear over 66in panel height
5000 lb/in x 66in = 330,000 lbs = Pn required
11 bolts on 6in centers

Pn/bolt = 330,000lbs / 11 bolts
Pn/bolt = 30,000 lbs required

Pn/bolt = Fnv · Ab
= 72,000psi · 0.442 in^2

Pn/bolt = 31,824 lbs actual

Pn act/bolt > Pn req/bolt
31,824lbs > 30,000 lbs ✓

Pn act/bolt x 11 bolts
31,824lbs x 11 bolts = 350,064 lbs = Pn actual

Pn actual > Pn required
350,064 lbs > 330,000 lbs ✓

$\boxed{\therefore \text{ 11 3/4" Grade 5 bolts on 6in centers}}$ ok

CRSI

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Project		Sheet No. of
Made By	Checked By	Date
Subject		Project No.

Tension Capacity (failure)

$P_n = F_{nt} A_b$

$= 120{,}000\,psi \times 0.442\,in^2$

$P_n = 53040\ lbs/bolt$

$P_n \times 11\ bolts$

$53040\ lbs/bolt \times 11$

$P_n = 583440\ lbs$

Yield Strength ([illegible])

$P_n = F_y A_b$

$= 92{,}000\,psi \times 0.442\,in^2$

$P_n = 40{,}664\ lbs/bolt$

$P_n \times 11\ bolts$

$40{,}664\ lbs/bolt \times 11\ bolts$

$P_n = 447{,}304\ lbs$

The bolt design for the polycarbonate safe haven wall was developed using ProEngineer, ANSYS Autodyne Explicit Dynamics, and the American Institute of Steel Construction manual. The design started by developing a model in ANSYS to calculate the required shear force to be resisted by the bolts. The safe haven wall is required to resist a 15 psi load applied directly to the polycarbonate panels. A 30 psi load was decided upon to be applied with a dynamic load factor of 2, yielding a total load of 60 psi and a safety factor of 4. The design was developed in ProEngineer and imported into ANSYS where the loading was applied. The sides of the panel were fixed to simulate the design in an actual field test. Figure D1 belows shows how the design looks in ANSYS.

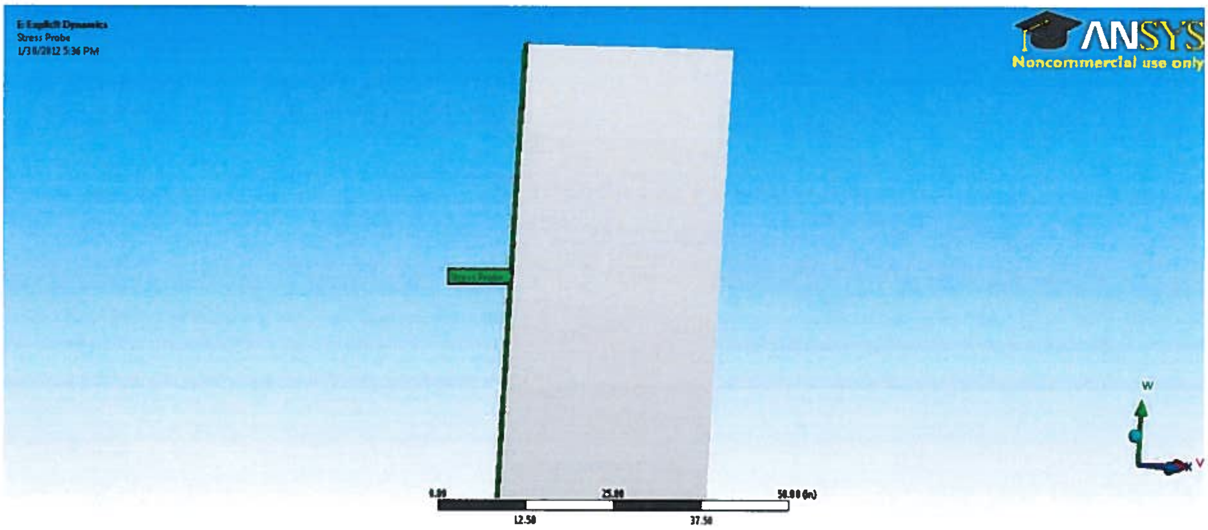

Figure D1: Design in ANSYS used to provide shear stresses in panel

A stress probe parameter in the model was used to calculate the resulting shear stress of 5000 psi along the edge of the panel. Figures D2-4 below further illustrate the results from the modeling providing the 5000 psi shear stress.

Definition	
Type	Stress
Location Method	Geometry Selection
Geometry	1 Face
Orientation	Global Coordinate System
Options	
Result Selection	Normal - Y Axis
Display Time	0.11 s
Spatial Resolution	Use Maximum
Results	
Maximum Value Over Time	
Normal - Y Axis	4985.5 psi
Minimum Value Over Time	
Normal - Y Axis	0. psi
Information	

Figure D2: Details of the maximum shear stress over time

Tabular Data

	Time [s]	Stress Probe (NormY) [psi]
1	1.1755e-038	0.
2	1.0001e-002	390.31
3	2.0003e-002	1375.
4	3.0001e-002	3019.1
5	4.0002e-002	2363.4
6	5.0002e-002	2246.7
7	6.e-002	2559.4
8	7.0003e-002	2995.3
9	8.0004e-002	3470.2
10	9.e-002	4051.3
11	0.1	4831.3
12	0.11	4985.5
13	0.12	4806.5
14	0.13	4458.4
15	0.14	4037.6
16	0.15	3506.
17	0.16	2807.4
18	0.17	2144.3
19	0.18	2087.3
20	0.19	1391.6
21	0.2	681.84

Figure D3: Table of the shear stress versus the model run time

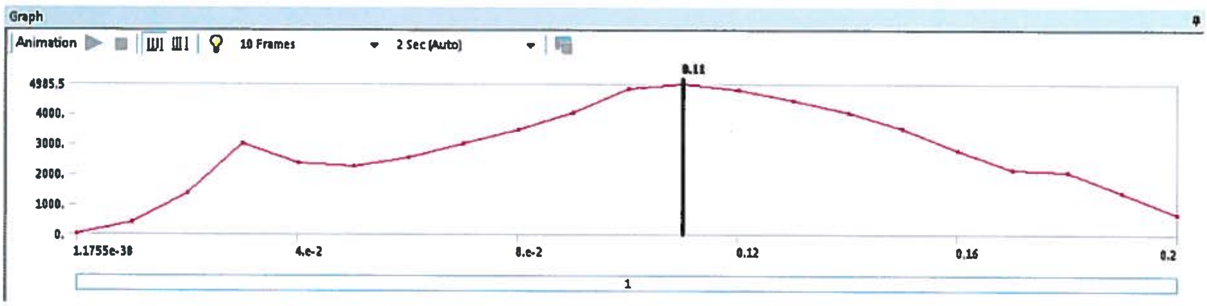

Figure D4: Graph of shear stress versus model run time

With the shear stress known, it was used to calculate the nominal shear load used for calculating the shear load each bolt must resist. Since the 5000 psi stress occurs along the panel edge, the shear load was calculated by multiplying by the 1 inch panel thickness and 66 inch height. In turn, the shear load was calculated to be 330,000 lbs. This shear load divided by the number of bolts, 11, gave the required load each bolt must withstand. From here, the actual strength each bolt can resist was calculated using the shear stress of the bolts provided by the Machinery's Handbook 28th edition and the AISC steel construction manual equations. The shear stress of a ¾ inch grade 5 bolt is 60% of its tensile strength which is 120 ksi; therefore, the shear stress is 72 ksi. The shear stress multiplied by the area of one bolt is equal to the load that one bolt can resist. The actual shear stress must be larger than the required shear stress in order for the design to pass. Since the actual is greater than the required shear stress the design is good. The calculation for tensile and yield stress for each bolt is the same except for using the tensile and yield stresses given in the handbook. The completed calculations can be seen below.

Appendix E

The deflection comparison between the blast testing and the ANSYS model were performed using the deflection laser data and the displacements found by importing the pressures created during blast testing into ANSYS. The comparisons were performed for four blast tests with each test measuring the deflection of a different component of the safe haven wall. The deflections comparisons can be seen in Figures E1 – E4. The curves comparing the deflection of the polycarbonate material in Figures E1 and E4 match quite well with the exception of the deflections being higher in the ANSYS models. This is most likely a result of the polycarbonate material model used in ANSYS not being as current or strong as the newer technology Makrolon Hygard polycarbonate provides.

The deflection comparison of the curves in Figure E2 and E3 are the result of blast testing on the steel frame component of the wall. These curves only show slight consistency with each other in displacement trend. This is most likely due to the steel frame of the wall being bolted to an I-beam, thus allowing for a pivoting action to occur during testing. The pivoting action allows the whole frame to move much more than if it was bolted to the roof of a mine. In turn, the deflection of the steel is much more when compared to the fixed conditions of the frame in the ANSYS model. The steel frame deflection is also hindered by the fact that it was bolted together allowing for system to absorb more blast energy in multiple bolted connections compared to the fully bonded system used in ANSYS.

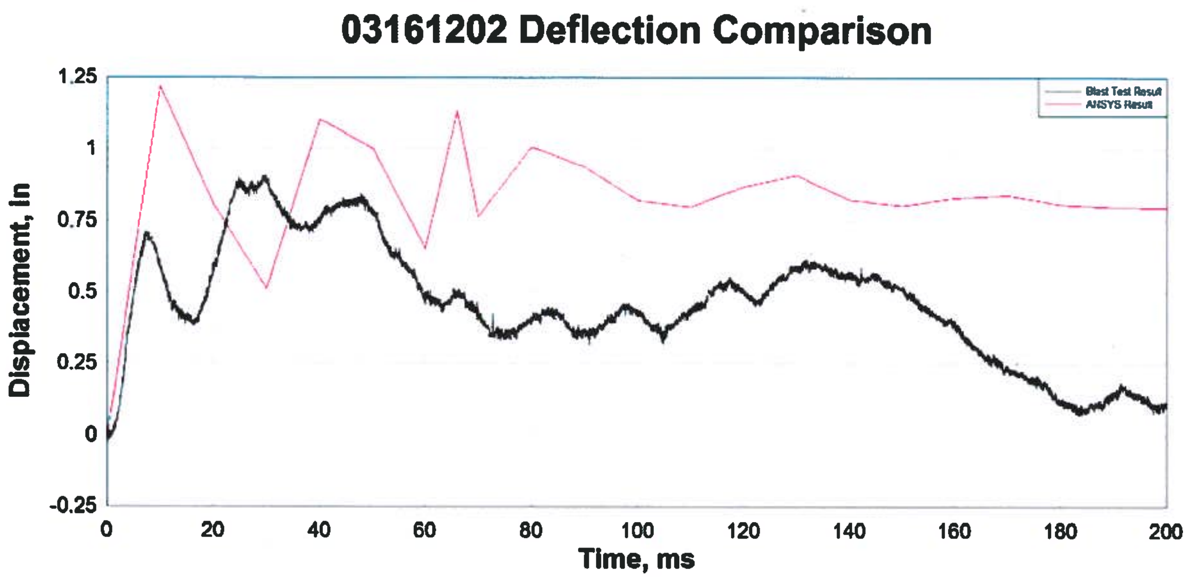

Figure E1 – Test 03161202 Displacement Comparison of Center Polycarbonate Panel

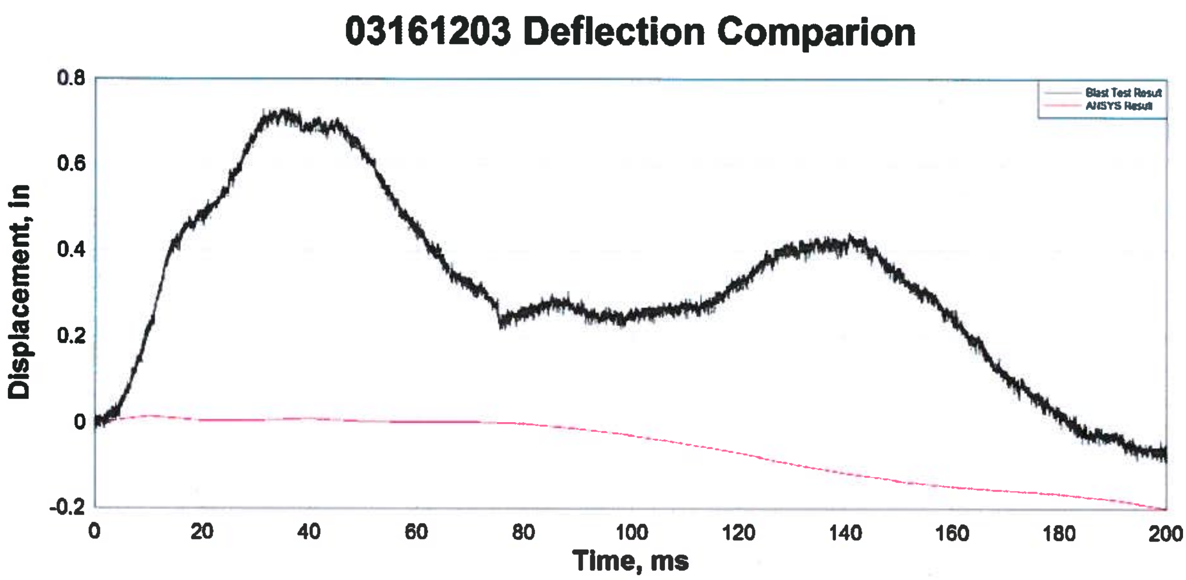

Figure E2 – Test 03161203 Deflection Comparison of Left-Center Vertical Upright

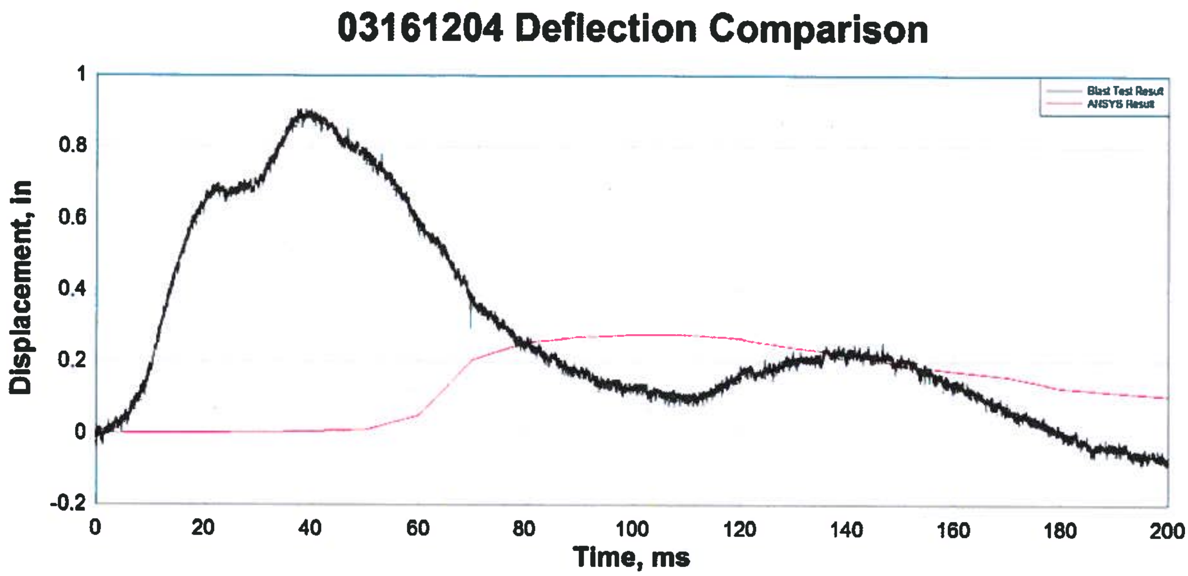

Figure E3 – Test 03161204 Deflection Comparison of Far Left Vertical Upright

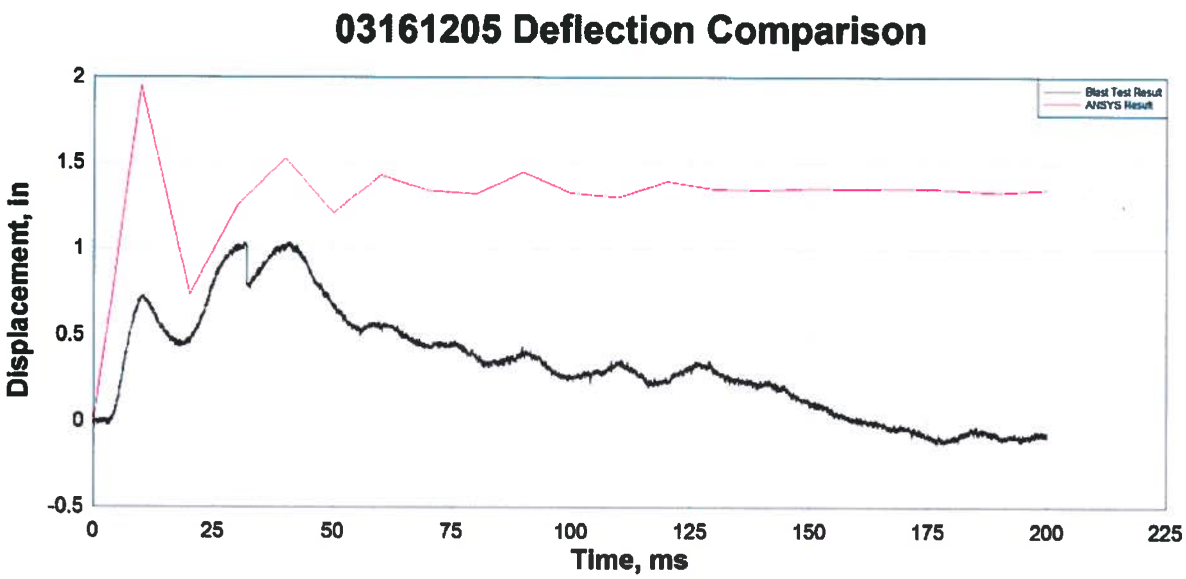

Figure E4 – Test 03161205 Deflection Comparison of Left Polycarbonate Panel